FINAL REPORT

Enhancement of the FDOT's Project Level and Network Level Bridge Management Analysis Tools

Contract No. BDK83 977-01

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Florida Department of Transportation
Tallahassee, FL 32309

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DISCLAIMER

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
in	Inches	25.4	millimeters	mm
ft	Feet	0.305	meters	m
yd	Yards	0.914	meters	m
mi	Miles	1.61	kilometers	km

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
AREA				
in^2	Square inches	645.2	square millimeters	mm^2
ft^2	Square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or	Mg (or "t")

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
TEMPERATURE (exact degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003).

APPROXIMATE CONVERSIONS FROM SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
mm	millimeters	0.039	inches	in
m	Meters	3.28	feet	ft
m	Meters	1.09	yards	yd
km	kilometers	0.621	miles	mi

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
AREA				
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	Hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	Liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
MASS				
g	Grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric	1.103	short tons (2000	T

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
TEMPERATURE (exact degrees)				
^{o}C	Celsius	1.8C+32	Fahrenheit	^{o}F

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
ILLUMINATION				
lx	Lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
FORCE and PRESSURE or STRESS				
N	Newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003).

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16. Abstract

Over several years, the Florida Department of Transportation (FDOT) has been implementing the AASHTO Pontis Bridge Management System to support network-level and project-level decision making in the headquarters and district offices. Pontis is an integral part of a Department-wide effort to improve the quality of asset management information provided to decision makers. With the success of these previous research efforts, FDOT further investigated several additional modeling issues that were not possible during earlier Pontis implementation work.

First, a sensitivity analysis was performed on the Project Level Analysis Tool (PLAT) and Network Analysis Tool (NAT), as well as a comparison made between the PLAT and NAT models and the National Cooperative Highway Research Program (NCHRP) Report 590, which explored the criteria used for priority setting and resource allocation. The analysis suggested priority enhancements to PLAT/NAT, including improved deterioration and cost models, and multi-objective optimization. Secondly, an improved version of the NBI Translator has been developed and implemented using two years of bridge inspection data from the Florida bridge inventory. A standalone computer program was developed, as well as a Microsoft Excel spreadsheet version of the Translator program written in Visual Basic for Applications (VBA), which was incorporated into the PLAT.

Next, the research developed improved deterioration, action effectiveness, and cost models for Pontis and the PLAT. A new, simplified procedure was developed for estimating one-step Markovian models that produces usable results with significantly smaller sample sizes than traditional regression. As the fifth accomplishment, models were developed for estimating user costs at bridge sites where no detour is considered. Several existing user cost models were reviewed in the study, including some traditional roadway-based models and the previous FDOT user cost model for bridges. New accident models were formulated based on Florida crash data at bridge sites for years 2003 through 2007, including the following: binomial logistic regression, Poisson regression, and negative binomial regression models.

17. Key Words
Bridges, deterioration, effectiveness, condition ratings, accidents, models, and sensitivity analyses.

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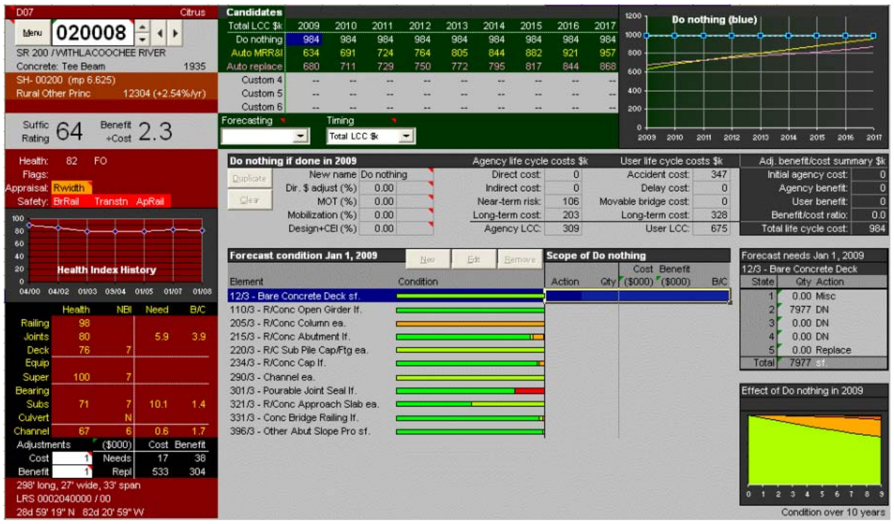
EXECUTIVE SUMMARY

Since 1997, the Florida Department of Transportation (FDOT) has been implementing the AASHTO Pontis Bridge Management System to support network-level and project-level decision making in the headquarters and district offices. Pontis is an integral part of a Department-wide effort to improve the quality of asset management information provided to decision makers. The credibility and usefulness of this information is also essential for satisfaction of the requirements of the Government Accounting Standards Board Statement 34 (GASB 34) regarding the reporting of capital assets. Previous Department research in the areas of user costs and agency costs have identified the analytical needs for implementation of the economic models of Pontis, and have made significant progress in the development of these models. A spreadsheet-based Project Level Analysis Tool (PLAT) has been developed to process and present Pontis analytical results in a form useful for bridge-level decision making. A network-level programming and budgeting decision support tool was also developed to use the PLAT results to develop system-wide estimates of funding needs and performance expectations.



D07

020008

SR 200 / WITHLACOOCHEE RIVER

Concrete: Tee Beam 1935

SH- 00200 (mp 6.625)

Rural Other Princ 12304 (+2.54%/yr)

Suffic Rating 64

Benefit +Cost 2.3

Health: 82 FO

Flags:

Appraisal: Rwidth

Safety: BrRail Transtn ApRail

	Health	NBI	Need	B/C
Railing	98			
Joints	80		5.9	3.9
Deck	76	7		
Equip				
Super	100	7		
Bearing				
Subs	71	7	10.1	1.4
Culvert		N		
Channel	67	6	0.6	1.7

Adjustments		($000)	Cost	Benefit
Cost	1	Needs	17	38
Benefit	1	Repl	533	304

298' long, 27' wide, 33' span

LRS 0002040000 / 00

28d 59' 19" N 82d 20' 59" W

Candidates

Total LCC $k	2009	2010	2011	2012	2013	2014	2015	2016	2017
Do nothing	984	984	984	984	984	984	984	984	984
Auto MRR&I	634	691	724	764	805	844	882	921	957
Auto replace	680	711	729	750	772	795	817	844	868
Custom 4	--	--	--	--	--	--	--	--	--
Custom 5	--	--	--	--	--	--	--	--	--
Custom 6	--	--	--	--	--	--	--	--	--

Timing: Total LCC $k

Do nothing if done in 2009

New name: Do nothing

Dir. $ adjust (%): 0.00

MOT (%): 0.00

Mobilization (%): 0.00

Design+CEI (%): 0.00

Agency life cycle costs $k	
Direct cost:	0
Indirect cost:	0
Near-term risk:	106
Long-term cost:	203
Agency LCC:	309

User life cycle costs $k	
Accident cost:	347
Delay cost:	0
Movable bridge cost:	0
Long-term cost:	328
User LCC:	675

Adj. benefit/cost summary $k	
Initial agency cost:	0
Agency benefit:	0
User benefit:	0
Benefit/cost ratio:	0.0
Total life cycle cost:	984

Forecast condition Jan 1, 2009

Element	Condition
12/3 - Bare Concrete Deck sf.	
110/3 - R/Conc Open Girder lf.	
205/3 - R/Conc Column ea.	
215/3 - R/Conc Abutment lf.	
220/3 - R/C Sub Pile Cap/Ftg ea.	
234/3 - R/Conc Cap lf.	
290/3 - Channel ea.	
301/3 - Pourable Joint Seal lf.	
321/3 - R/Conc Approach Slab ea.	
331/3 - Conc Bridge Railing lf.	
396/3 - Other Abut Slope Pro sf.	

Scope of Do nothing

Action	Qty	Cost ($000)	Benefit ($000)	B/C

Forecast needs Jan 1, 2009

12/3 - Bare Concrete Deck

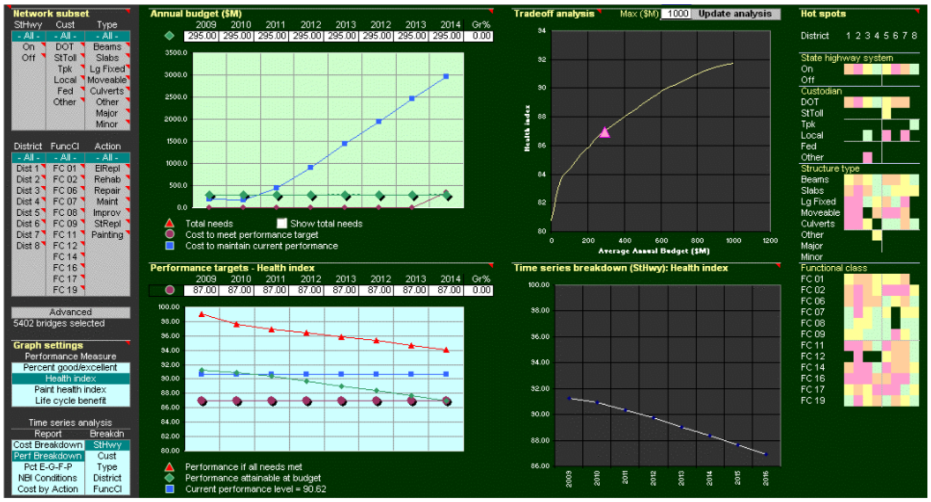
State	Qty	Action
1	0.00	Misc
2	7977	DN
3	0.00	DN
4	0.00	DN
5	0.00	Replace
Total	7977	sf.

With the success of these previous research efforts, FDOT further investigated several additional modeling issues that were not possible during earlier Pontis implementation work. The Department now had enough element-level bridge inspection data to perform a rigorous analysis of bridge deterioration, for use in forecasting life cycle costs for planning of maintenance, repair, rehabilitation, and replacement work. The database also makes it possible to improve the forecasting of National Bridge Inventory bridge condition measures, by improving the translation of forecast element condition states into the summary NBI condition ratings. This modeling effort will result in improved capabilities needed for the Pontis bridge management system and the FDOT Project Level Analysis Tool, and a report describing the methodology and updating procedures for future use by the Department.

The products will be immediately used by the headquarters Maintenance Office and by the District Structures and Maintenance Engineers in the Department's maintenance planning processes, and will be of great interest to the entire national bridge management community beyond Florida. Overall, the conducted research will have a direct influence on the efficiency and effectiveness of the capital and maintenance program for bridges. This means the research products can potentially save a significant amount of money, or deploy the funding more effectively, every year.

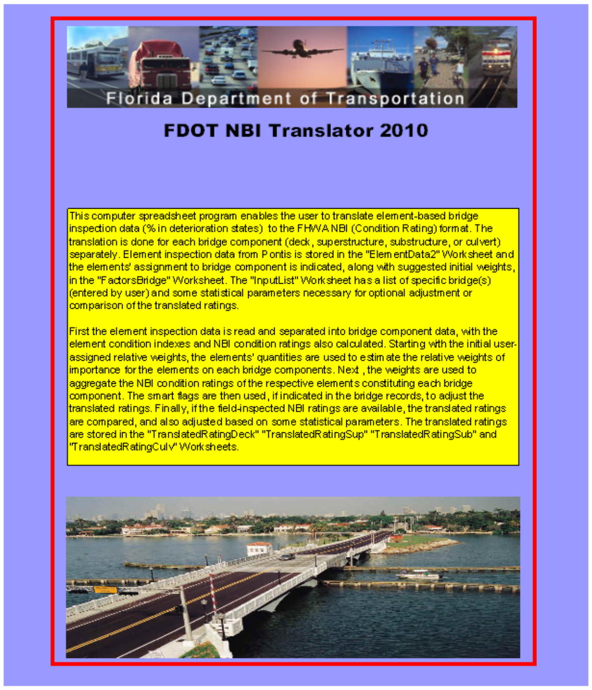
The major accomplishments of this study are summarized in the following paragraphs.

Sensitivity Analyses of PLAT and NAT



A sensitivity analysis was performed on the Project Level Analysis Tool (PLAT) and Network Analysis Tool (NAT), and these tools were also compared to the products of National Cooperative Highway Research Program (NCHRP) Project 12-67, which explored the criteria used for priority setting and resource allocation. The products of NCHRP Project 12-67 were published in Report 590, including a software system developed to demonstrate the multi-objective concept using Pontis data. This product is called the Multi-Objective Optimization System (MOOS). It was observed that PLAT/NAT is quite sensitive to deterioration and unit costs. MOOS was subjected to a more limited sensitivity analysis with Florida data and found to be equally sensitive to these inputs. It was observed that the forecasts of deterioration of bridges in new condition were unrealistically fast, and that this was having a substantial effect on the needs analysis and programming model in NAT. This indicated the importance of gaining a more confident quantitative understanding of deterioration of bridges in relatively good condition.

The PLAT/NAT was found to recommend more element replacement projects (rather than repairs and rehabilitation) than would be realistic. Some of the projects also had unrealistically low cost estimates. Neither PLAT/NAT nor MOOS was able to maintain the present health index of 90.62 under the default Florida deterioration model. However, MOOS gives more control over this result because of its use of a multi-objective utility function, which simultaneously considers life cycle cost, condition, and other potential project benefits. Giving more weight to health index, relative to life cycle cost, invariably led to better ending conditions. A simple utility function capability, that combines only life cycle cost and health index, could be added to the PLAT/NAT system and would significantly improve policy sensitivity. A risk model, which considers the response to natural and man-made hazards such as scour and fatigue, would also vastly improve policy sensitivity.



FDOT NBI Translator 2010

This computer spreadsheet program enables the user to translate element-based bridge inspection data (% in deterioration states) to the FHWA NBI (Condition Rating) format. The translation is done for each bridge component (deck, superstructure, substructure, or culvert) separately. Element inspection data from Pontis is stored in the "ElementData2" Worksheet and the elements' assignment to bridge component is indicated, along with suggested initial weights, in the "FactorsBridge" Worksheet. The "InputList" Worksheet has a list of specific bridge(s) (entered by user) and some statistical parameters necessary for optional adjustment or comparison of the translated ratings.

First the element inspection data is read and separated into bridge component data, with the element condition indexes and NBI condition ratings also calculated. Starting with the initial user-assigned relative weights, the elements' quantities are used to estimate the relative weights of importance for the elements on each bridge components. Next , the weights are used to aggregate the NBI condition ratings of the respective elements constituting each bridge component. The smart flags are then used, if indicated in the bridge records, to adjust the translated ratings. Finally, if the field-inspected NBI ratings are available, the translated ratings are compared, and also adjusted based on some statistical parameters. The translated ratings are stored in the "TranslatedRatingDeck" "TranslatedRatingSup" "TranslatedRatingSub" and "TranslatedRatingCulv" Worksheets.

Improved NBI Translator

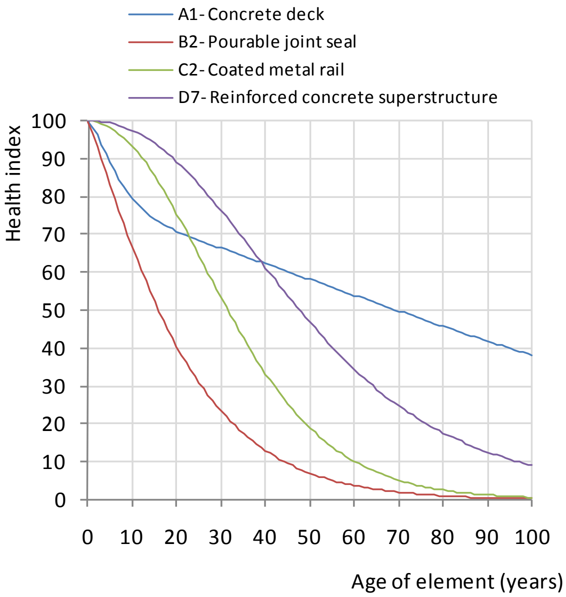
An improved version of the NBI Translator was developed using two years of bridge inspection data from the Florida bridge inventory. A standalone computer program was developed, as well as a Microsoft Excel spreadsheet version of the Translator program written in Visual Basic for Applications (VBA). The latter was incorporated into the PLAT. The main concept in the NBI Translator is to estimate a single condition rating for a bridge component (deck, superstructure, or substructure) based on an aggregation, using relative weights, of the condition data of constituting bridge elements. Extensive research effort was expended in estimating the relative weights of the elements, including use of statistical multiple regression and optimization. It was concluded that element relative weights are best done using user-defined importance factors and consideration of the element quantities as well as the unit of measure. Optimal coefficients were obtained for estimating element condition indexes and converting these indexes to NBI ratings. But NBI rating 7 was observed as the predominant NBI rating even for excellent condition bridge components and their elements; this produced coefficients that force most of the translated ratings to NBI rating 7.

This problem is similar to that of FHWA's existing NBI Translator. It arises because of the fact that bridge age and other factors unrelated to measured condition data also affect the ratings assigned by trained bridge inspectors. Calibration of the original translated ratings was done using factors obtained from statistical regression of the data on inspected ratings and translated ratings. During the development of the Translator program, reviews of the initial translated ratings involving case studies at specific bridges were done and the algorithms adjusted as necessary to improve the accuracy of the translated ratings. Case studies were also done on the final Excel version of the NBI Translator, reviewing the translation process at randomly selected bridges. The deterioration models of bridge components and elements were also formulated based on the translated ratings. Overall, the accuracy of the translated ratings, when compared to actual NBI inspected ratings, is significantly better than the FHWA's NBI Translator, and also improved over the previous model of the NBI Translator developed for Florida.

The translation accuracy was generally very good for bridges in NBI ratings 6 or higher, and relatively poor for bridge components or culverts in NBI ratings less than "6." Most bridges in the Florida inventory considered (2007 and 2008 inspections) are in NBI ratings "6" or higher, with roughly about 95% for each of the bridge components decks, superstructures, and substructures, and culverts. Given that there are fewer than about 5% of the bridges in the inventory with NBI condition ratings less than or equal to "5," the results should be considered reasonably accurate for the overall bridge inventory. Calibration (with regression factors) of the original translated ratings was observed to significantly improve the accuracy of translation on individual bridge components, with about 90% of the bridges having errors less than or equal to one.

The following additional general observations also were made during the study: state-maintained bridges can be better translated than other bridges; slabs should be considered as both deck and superstructure elements on the bridges; condition of substructures associated with culverts do not necessarily affect the overall condition index or NBI rating of the culvert; not all translation errors can be explained quantitatively; translation errors cannot be significantly related to bridge or roadway attributes; and the proposed NBI Translator Program can be accurately used to develop deterioration models of the bridge components and the elements.

Improved Deterioration and Action Effectiveness Models



In another task, the research developed improved deterioration and action effectiveness models for Pontis and the Project Level Analysis Tool. A new, simplified procedure was developed for estimating one-step Markovian models that produces usable results with significantly smaller sample sizes than traditional regression. This enabled the estimation of models for even relatively uncommon elements. It was found that the new inspection-based models showed deterioration rates far slower than the expert elicitation models that have been used to date. While this had been predicted by practitioners in the field, the magnitude of the discrepancy will be strong motivation for other states to estimate their own statistical models.

A new analysis method was developed to model the onset of deterioration, i.e., the period when a bridge is new, before it starts to exhibit visible defects. It was found that the onset of deterioration is age-dependent, and that a Weibull survival probability model provided a relatively simple and useful way of describing the effect of bridge age. The Weibull model is compatible with the Markov model currently used in Pontis, and was shown to improve on the accuracy of Markov model predictions.

A new methodology was also developed for the estimation of action effectiveness models, which overcomes many of the problems that have been noted in past efforts. A complete set of models was estimated from historical activity and condition data, with the activity data drawn from Florida's maintenance management system and its AASHTO Trns•Port database. It was found that the actual effectiveness of Florida DOT repair and rehabilitation actions is greater than had been estimated by the panel of experts that originally estimated Florida's models in 2001. As with the deterioration model, the new action effectiveness model greatly improved the realism of condition predictions in Pontis and PLAT/NAT because of the greater use of historical bridge inspection data.

Validation of Cost Models

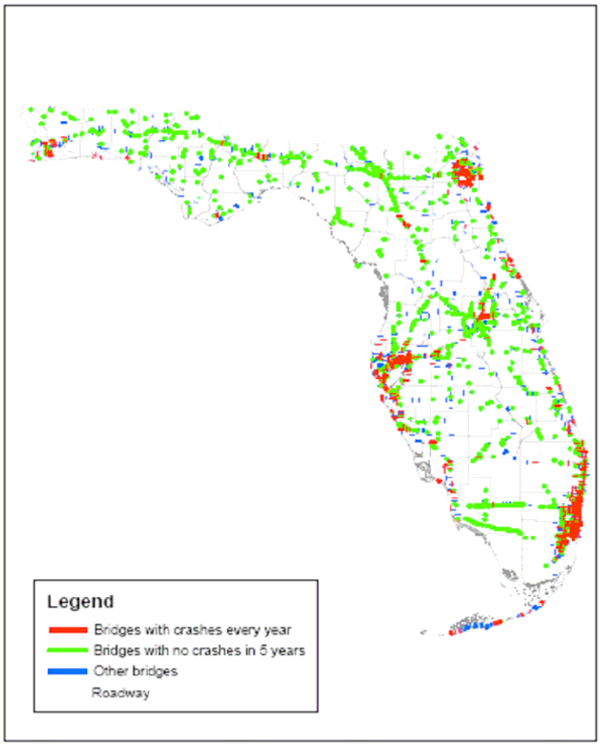
Another major accomplishment was a validation of cost models for the Florida Pontis and PLAT/NAT models, using three main sources of data: Statewide construction bids database (AASHTO Trns*port); FDOT District Bridge Construction Bids Records; and the FDOT Work Library-MMS Cost data (or MMS) on bridge-related maintenance work. Project costs were compiled and summarized by work types and unit costs were estimated where possible, in the bridge/element/action format, compatible with the Pontis Bridge Management System. Relationships between the costs and bridge attributes were also investigated and findings reported. The bridge cost data utilized in the study are available in electronic format, for both the raw data and final results.

As expected, the bid data contributed to a majority of the replacement and rehabilitation actions while the MMS cost database provided cost for much of the repair and maintenance actions. The former are basically contractors' bids to perform construction services on the bridge, and can be considered very reliable. On the other hand, MMS costs needed to be "cleaned up" before use in the Pontis BMS. An example of such "cleaning up" involved estimating the "trimmed" mean, This involves estimating the mean of the interior portion of data by excluding outliers, specified as percentage of the data from the top and bottom tails of the data set.

A review and some analyses were also done on the Department's current use of MMS in capturing bridge action costs, which relies primarily on the MMS activity number to identify the work done to the bridge. The discussions and results are provided, including mean unit costs, bridge ages at actions, etc., as well an investigation on the matches between the Activity Numbers (as recorded in MMS) and the Pontis-compatible Action subcategories. This is important because the MMS cost database is currently the FDOT's primary source for its annual reports on bridge maintenance and repair expenditures, and the costs are typically summarized by the MMS Activity Numbers.

Overall, many useful cost data were obtained in this study, but the more useful estimates appear to be for project level actions rather than the bridge element actions. In other words, good estimates were derived for projects such as cathodic protection and painting projects on a bridge, rather for the specific element actions for cathodic protection of the bridge substructure element or structural painting of the bridge superstructure element. These project costs may typically include other cost items such as mobilization, maintenance of traffic, and even some other element actions. Meaningful statistical relationships were also established between costs and bridge attributes, including age of bridge at which work was done, as well as relationship between Maintenance of Traffic (MOT) costs and traffic characteristics of the "under roadways". In the review of bid costs at a specific FDOT district, it was observed that on bridge rehabilitation and replacement projects, structures cost was the predominant portion of the total costs, constituting between 67% and 91% of the total project costs; Maintenance of Traffic (MOT) costs were between 1% and 14%; while Mobilization costs ranged from 3% to 13%.

Accident and User Cost Models



As another accomplishment of the study, models were developed for estimating user costs at bridge sites where no detour is considered. Several existing user cost models were reviewed in the study, including some traditional roadway-based models and the previous FDOT user cost model for bridges. Three primary components of the user costs modeled were the following: time travel costs; vehicle operating costs; and accident costs. Traditionally, user costs components, especially, the first two mentioned here are greatly influenced by detour lengths. But in this study, detour lengths were not used as input variables, but rather, the influencing variables are bridge deck surface roughness, bridge width, bridge length, and traffic-related attributes. Travel time costs are based on delays experienced by users on the bridges, when compared to the speed of travel on the adjacent roadways. Vehicle operating costs are also incurred by users due to the effect of speed changes, delays, fuel costs, and miscellaneous costs of maintenance, repair, etc. While the computations of these two categories are straightforward, estimating the accident-related user cost is relatively more challenging. The existing user cost model by Thompson (1999) was extensively reviewed and used to investigate new models of estimating accident-related user costs.

New models were formulated based on Florida crash data at bridge sites for years 2003 through 2007, in an effort to improve on the Thompson (1999)'s model. Also, more rigorous models were investigated, including binomial logistic regression, Poisson regression, and negative binomial regression models for accident prediction. The binomial logistic regression model predicts if a crash will occur or not at a particular bridge site, as well as a probability of the occurrence of the accident. The binomial logistic regression model developed on the study was able to relatively predict better the non-occurrence of crashes, than their occurrence. The Poisson model did not fit the crash data well, and the models' results were not useful.

On the other hand, the negative binomial regression model was better fitted to the crash data. An effort to improve these models included incorporation of some variables such as driver's age and time of crash, as typically used in the roadway crash models. These were found to improve these models a little bit, but as expected, they are of no practical use since they cannot be used in real applications to predict crashes at bridge locations. But this shows that to actually understand and model the causes of crashes, both at bridge locations and on the roadways in general, more variables are needed apart from the geometric attributes typically considered in bridge crash models. Finally, a comparison is made between prediction accuracy of the negative binomial model with an updated version of the existing linear regression model. The accident data for years 2003 to 2006 were utilized to develop the models, and predict the accident counts for 2007. The actual or observed data for 2007 were compared to the predicted data to estimate errors of prediction. Within an error of one accident count, the negative binomial was more accurate than the linear model.

Conclusions

As described above in the various sections, this study was able to successfully investigate and develop several additional models to further enhance the implementation of Pontis at FDOT, including the following: the Project Level Analysis Tool (PLAT) and Network Analysis Tool (NAT); improved version of the NBI Translator; improved deterioration, action effectiveness, and cost models for Pontis and the PLAT; and user cost models at bridge sites where no detour is considered.

Some of the final deliverables include the following: Revised Project Level Analysis Tool (PLAT), an Excel file; Revised Network Analysis Tool (NAT), an Excel file; PLAT Results File, a Microsoft Access database; Revised PLAT Users Manual, delivered in Microsoft Word and Acrobat formats; Revised NAT Users Manual, delivered in Microsoft Word and Acrobat formats; a PowerPoint file used in the PLAT/NAT training class; and an Excel file containing database update scripts to facilitate the updating of FDOT's main Pontis database with the quantitative results of this study.

None of the work presented here on investment decision rules can yet be considered to be a recommendation, primarily because the need for improvement in the benefit model is so clear. It is likely that priorities expressed by the models will change once a multi-objective analysis is introduced. The recently initiated study to develop risk models will be an important enhancement.

In the meantime, the improved PLAT/NAT model would benefit from a review by FDOT staff of the reasonableness of the results so far, especially at the project level. The multi-objective aspect introduced by the risk models offers great potential for adjusting the relative sensitivity of the models to various policy goals, and also provides opportunities for improvement of important sub-models such as indirect cost and scale feasibility.

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Software and Miscellaneous Deliverables (separate from this final report):

- Revised Project Level Analysis Tool (PLAT), an Excel file.
- Revised Network Analysis Tool (NAT), an Excel file.
- PLAT Results File, a Microsoft Access database.
- Revised PLAT Users Manual, delivered in Microsoft Word and Acrobat formats.
- Revised NAT Users Manual, delivered in Microsoft Word and Acrobat formats.
- A Powerpoint file used in the PLAT/NAT training class.
- An Excel file containing database update scripts to facilitate the updating of FDOT’s main Pontis database with the quantitative results of this study.

LIST OF TABLES

LIST OF FIGURES

1. Introduction

Since 1997, the Florida Department of Transportation (FDOT) has been implementing the AASHTO Pontis Bridge Management System to support network-level and project-level decision making in the headquarters and district offices. Pontis is an integral part of a Department-wide effort to improve the quality of asset management information provided to decision makers. The credibility and usefulness of this information is also essential for satisfaction of the requirements of the Government Accounting Standards Board Statement 34 (GASB 34) regarding the reporting of capital assets. Previous Department research in the areas of user costs and agency costs have identified the analytical needs for implementation of the economic models of Pontis, and have made significant progress in the development of these models. A spreadsheet-based Project Level Analysis Tool (PLAT) has been developed to process and present Pontis analytical results in a form useful for bridge-level decision-making. A network-level programming and budgeting decision support tool was also developed to use the PLAT results to develop system-wide estimates of funding needs and performance expectations.

With the success of these previous research efforts, FDOT further investigated several additional modeling issues that were not possible during earlier Pontis implementation work. The Department now had enough element-level bridge inspection data to perform a rigorous analysis of bridge deterioration, for use in forecasting life cycle costs for planning of maintenance, repair, rehabilitation, and replacement work. The database also makes it possible to improve the forecasting of National Bridge Inventory bridge condition measures, by improving the translation of forecast element condition states into the summary NBI condition ratings. This modeling effort will result in improved capabilities needed for the Pontis bridge management system and the FDOT Project Level Analysis Tool, and a report describing the methodology and updating procedures for future use by the Department.

The products will be immediately used by the headquarters Maintenance Office and by the District Structures and Maintenance Engineers in the Department’s maintenance planning processes, and will be of great interest to the entire national bridge management community beyond Florida. Overall, the conducted research will have a direct influence on the efficiency and effectiveness of the capital and maintenance program for bridges. This means it can potentially save a significant amount of money, or deploy the funding more effectively, every year.

1.1 Research Objectives and Tasks

The study objectives and main tasks can be summarized as follows:

- Determine sensitivity of the Project Level Analysis Tool (PLAT) and Network Analysis Tool (NAT) to various inputs such as deterioration models for significant elements and action types and PLAT decision rules.
- Compare results of PLAT and NAT with NCHRP 12-67 Multi-Objective Optimization for Bridge Management Systems.
- Create an improved method of translating element level data to condition state ratings. (NBI translator)
- Update deterioration models based on FDOT history of element level inspection.
- Validate FDOT cost models and update as required.
- Modify PLAT to perform agency cost analysis only.
- Develop user cost model for when no detour exists.

- Modify PLAT and NAT software based on results of this research project.
- Develop investment decision rules based on the research and enhanced software.
- Conduct training workshop and prepare final report.

1.2 Report Organization

This report begins with a brief introduction and description of research objectives and tasks as already presented in this section. Next, section 2 presents the results from first two main tasks, i.e., conduct sensitivity analysis on PLAT and NAT, and also compare results of PLAT and NAT with NCHRP 12-67 results. In section 3, the efforts on developing an improved NBI Translator are presented, while section 4 describes the development of improved bridge deterioration models, including action effectiveness models. Using primarily historical data in Florida, the validation of bridge cost models and update in Pontis are presented in section 5. Next, the formulation of user cost models for bridges is discussed in section 6, for special cases when travel detour is not available or not being considered. In section 7, results and some deliverables from the research project are presented, including the following: modifying PLAT and NAT software based on results of this research project; developing investment decision rules based on the research and enhanced software; and conducting a training workshop. Appendix A shows the pertinent literature references while other Appendixes B to D show supporting discussions, tables and figures to accompany various sections of the report.

2. Analyses and Review of Florida's PLAT and NAT

This section presents the results of a sensitivity analysis of the most important inputs to Florida's Project Level Analysis Tool (PLAT) (Sobanjo and Thompson 2004) and Network Analysis Tool (NAT) (Sobanjo and Thompson 2007). Also the PLAT and NAT were compared to the products of National Cooperative Highway Research Program (NCHRP) Report 590 (Patidar et al. 2007), which explored the criteria used for priority setting and resource allocation.

2.1 Sensitivity Analysis

There are several objectives for the sensitivity analysis:

- To ascertain the extent to which each input data set affects the outcome of the analysis;
- To determine whether there is any instability of results, in the form of large output changes relative to small input changes; and
- To inform priorities for further investigation in later tasks of the study.

In order to conduct the analysis, a sensitivity analysis framework was designed. This framework consists of a set of output measures to be tested across all scenarios; a set of procedures to calculate these measures; and a set of relationships between a vector of systematically varied parameters and the existing analytical process.

2.1.1 Framework

For comparison of scenarios, the essential output and outcome measures of PLAT and NAT were used:

- Selection of actions – The classification scheme of action categories, as used in PLAT and NAT, was used in order to characterize the nature of work recommended under each scenario. This is reported as a count of the number of projects generated in each category. Each bridge is classified according to the highest category of work making up the project. The order of categories, from highest to lowest, is:
  600 – Replace bridge
  500 – Improve
  100 – Replace element
  200 – Rehabilitate
  300 – Repair
  400 – Maintain
- Initial cost – Project costs are estimated using the PLAT cost models with all Florida customizations. The PLAT Users Manual describes the methodology in detail.
- Benefit – This is expressed as the difference in life cycle cost between doing nothing over nine years, and taking the recommended action in the base year of the analysis. As in PLAT and NAT, a candidate must have positive benefits in order to be selected. Benefits include the savings in user costs of correcting functional deficiencies.
- Health index – Condition is represented by health index, using the same computational method as in the PLAT. In the PLAT and NAT, health index is presented at the beginning of each year, before any actions are taken in that

year. In order to gain a useful reflection of deterioration, the convention is established to use health index as forecast at the beginning of year 5.

Since the National Bridge Inventory Translator was found in earlier studies (Patidar et al. 2007, Sobanjo and Thompson 2007) to provide incorrect results, and is thus to be revised as part of the current study, this analysis does not use NBI performance measures such as condition ratings or sufficiency rating. Instead, condition is represented by means of the health index, and functional performance is included in life cycle benefits in the form of user costs (Thompson et al. 1999 and Sobanjo and Thompson 2004).

It was desired to employ a framework that provides a consistent and fair comparison across all inputs and all parametric values of each input. To maximize consistency, it was decided to use an unconstrained budget for every scenario, since a budget constraint would cause all scenarios to yield essentially the same costs. Therefore all outputs of the analysis are in the form of capital and maintenance needs in the base year.

Sixteen sets of scenarios were tested, reflecting the major areas where there may be significant uncertainty in input data:

- Deterioration. Systematic variation of deterioration rates for all elements were investigated first, followed by separate, more focused, investigations of deck elements, superstructure elements, and substructure elements.
- Initial cost. Systematic variation of unit costs in all action categories were investigated first, followed by separate investigations of the four preservation categories, functional improvements, and bridge replacement.
- Scale feasibility. Florida's customized model of scale feasibility was investigated by systematically varying the minimum threshold of the percent in condition states where each action is feasible. One analysis was conducted by varying all categories of actions, and then a second analysis was done by varying only the repair and rehabilitation actions.
- Paint system replacement. Florida has a customized scoping model for paint system replacement, which aggregates the painting needs across all painted steel elements on a bridge and then determines, based on a threshold percentage, whether the total weight of needs would justify total recoating rather than spot painting. The effect of varying the threshold was investigated.
- Deck replacement. PLAT has a scoping rule that includes, in any deck replacement project, the cost of replacing barriers, joints, and drainage systems. The effect was investigated of turning this rule on or off.
- Output quantities and costs. It is usually cost-effective, when visiting a structure to address a relatively poor condition state, to take advantage of the opportunity to address other deteriorated states on the same element, if this can be done with the same equipment and crew skills. PLAT provides five levels of scoping to progressively expand the scope of a project to handle preventive maintenance needs. The effect was investigated of stopping at each level.

For each of the first three groups of scenarios, the sensitivity analysis systematically generated 20 alternative levels of a sensitivity factor, referred to as cases. The base case presented the model inputs as currently used in the PLAT and NAT; typically 10 cases tested inputs lower than the base case; and 9 cases tested higher inputs. The PLAT software was modified to recalculate appropriate inputs as a function of the sensitivity parameter. This allowed related sets of input parameters to be varied in a consistent way. The later parts of this section describe how this was done for each group of scenarios.

The sensitivity analysis therefore consisted of 16 runs, most of which generated 20 cases for each bridge. To keep execution times reasonable, it was decided to analyze a 10% sample of bridges, and to exclude high-mast light poles, sign structures, mast arms, and retaining walls. The final sample consisted of 1182 bridges. The same sample of bridges was used in every case. The reported results were a simple count of projects by action category, a simple sum of costs and benefits, and an unweighted average of health index. These were computed for the sample only, and not scaled to represent the full inventory.

The PLAT software was modified to automate the generation and computation of cases. It was not necessary to make any changes to the NAT software. Total execution time for the analysis was approximately 140 hours. Methods and results for each group of scenarios are described in the following sections, with full results tabulated in Appendix B.

2.1.2 Deterioration

Like Pontis, the PLAT uses a Markovian deterioration model to forecast changes in condition over time. During the development of the NAT, it was found that deterioration from condition state 1 to condition state 2 was probably unreasonably fast (Sobanjo and Thompson2007). This same observation was made using other states' inventories in NCHRP Report 590 (Patidar et al. 2007), when investigating multi-objective optimization methods for bridge management systems.

As a result of the rapid initial deterioration, NAT is not able to produce solutions that sustain reasonably high network values of the health index, regardless of how much funding is allocated to the task. One possible solution is to lengthen the transition time from state 1 to state 2, thus slowing the initial rate of deterioration after an action is taken.

A Markovian deterioration model is expressed as a matrix of transition probabilities, as described in the PLAT Users Manual. If a unit of an element is in condition state 1, the probability of remaining in that state after one year is denoted as P_{11}. The probability of making a transition to state 2 in a year is denoted as P_{12}. If we ignore any possibility of transitioning from state 1 to state 3 or below in a single year, then $P_{12} = 1 - P_{11}$.

In a simple binary probability model like this, the median time to transition from state 1 to state 2 is easily computed from:

$$T = \frac{\log(0.5)}{\log(P_{11})} \tag{2.1}$$

This median transition time can then be adjusted upward (for slower deterioration) or downward (for faster deterioration) in a manner that is very intuitive. After adjusting the median transition time, the transition probabilities can be recomputed from:

$$P_{11} = 0.5^{(1/T')} \tag{2.2}$$

In this analysis only the transition from state 1 to state 2 is adjusted; all other transitions are held constant, except that the vector of transitions out of state 1 is normalized to sum to 100%. After some experimentation with different ways of generating 20 parametric adjustment factors for transition time, it was found that a multiplicative scale gave the most informative results over a wide distribution of possible values.

In the scale that was selected, the 11th of the 20 values was given the value 1.0, indicating that, for every element, the transition time (and therefore the transition probability matrix) would remain unchanged from the values already provided in the PLAT. Each successive value along the scale is 1.396 times the value before it. So the scale of adjustment factors ranges from 0.036 to 20.086. When presented on a graph, these points are evenly spaced on a logarithmic scale, as shown in Appendix B.

Appendix B1 shows the results when all elements are adjusted in this way. It was noted in working with the PLAT that the Pontis network optimization models (Cambridge 2001) tend to recommend doing nothing as an element deteriorates, until the element reaches its worst condition state. At that point the element is replaced. Appendix B1 quantifies this effect, showing that relatively few bridges have needs that are purely repair or rehabilitation.

Faster deterioration rates tend to produce more rehabilitation and repair projects, and fewer replacements. However, the absolute number of rehab and repair projects remains relatively small at all deterioration rates, indicating that this allocation of effort is more strongly governed by the long-term Pontis network optimization model than by the near-term life cycle cost model.

Relative to the current PLAT deterioration model, faster deterioration tends to increase the initial cost of work, as well as the life cycle benefit of doing the work. A slowing of deterioration has a much smaller economic effect: although fewer maintenance, repair, and rehab projects are generated, the cost savings is offset by greater reliance on replacement in the near term.

The health index graph in Appendix B1 shows that health index after 5 years is quite sensitive to deterioration rates. As expected, slower deterioration gives higher network average condition. It is interesting to note, however, that network average condition in the PLAT today, which is 87.0, would be increased only to 87.3 after 5 years using PLAT deterioration rates and an unlimited budget. A doubling of the transition time would increase this average only to 89.6.

It is likely that a greater reliance on repair and rehabilitation actions, which increase network condition at lower cost than replacement, would raise the network average health index more quickly. However, it would require a change in the network optimization model to make this happen, to give some weight to condition beyond what the life cycle cost model would give. This would cause the network optimization to place more reliance on preventive maintenance, to recommend do-something actions more often for condition states above the worst. This question will be investigated further in Section 3 (Deterioration and Action Effectiveness Models) of this report.

Appendices B2 through B4 break down the deterioration analysis by manipulating deck, superstructure, and substructure separately. An interesting and possibly unexpected result that is evident in these graphs is that changes in deterioration rates have a greater effect on substructures, bearings, and culverts, than on other parts of the bridge. A way to express this quantitatively is to compute the change in health index between a doubling and halving of the transition time from state 1 to state 2. This approximates the slope of the health index line in the vicinity of the current PLAT deterioration rates. These results are:

Decks, joints, railings	1.2
Superstructure and moveable bridge	0.9
Substructure, bearings, and culverts	2.6

By this measure, network condition is more than twice as sensitive to substructure deterioration as to deck deterioration, and almost three times as sensitive to superstructure deterioration rates.

2.1.3 Initial cost

Because the Pontis and PLAT models do not have fixed or non-linear costs, it is easy to conclude that changes in general levels of costs, that affect every aspect of the model by the same factor, will not change the selection of actions nor the benefit/cost ratios. The situation is more complicated, however, if we investigate changes in just one type of cost, causing one type of work to become more or less attractive relative to others.

Appendix B5 uses the same sensitivity factors as used for deterioration, but this time applies them directly to unit costs. Only preservation costs are adjusted, and only in the near-term PLAT model. So network optimization results, replacement costs, and improvement costs are held constant. This makes it possible to see the effects of the PLAT scoping models and the tradeoff between maintenance, repair, rehabilitation, and improvement (MRR&I), and Bridge Replacement.

As preservation costs increase, the number of preservation projects of all types is reduced. Since functional improvement projects usually also contain preservation work, they are also affected by the cost increase, so their frequency declines as well. Replacement, whose cost is not affected, thus gets more emphasis, winning more competitions against MRR&I.

As preservation costs decline from the levels currently used in the PLAT, the overall cost of needs also tends to decline slightly. The reason overall costs don’t decline faster, is the competition against do-nothing. With lower costs, a much greater number of cost-effective preservation projects are generated. This provides a significant increase in life cycle benefits and also a small overall increase in health index.

Interestingly, as costs increase from current PLAT levels, the overall trend in needs is downward also. The strongest impact is on repair and rehabilitation, which are pushed out of the program entirely. Life cycle benefits and health index decline. Far fewer projects are able to compete effectively against do-nothing.

With 1400 separate actions defined for Florida elements, the MR&R (maintenance, repair, and rehabilitation) action scheme is rather unwieldy for many purposes in the project-level analysis. Therefore a simpler scheme with only 50 sub-categories was defined, as shown in Figure 2.1 (Sobanjo and Thompson 2001). Each Pontis action is associated with one sub-category, serving to group similar actions together.

Appendices B6 through B9 break the preservation cost effect into action categories. These analyses behave exactly as expected. The action category whose cost is directly manipulated is very sensitive to changes in its cost, declining in frequency as its cost increases. Each category may be included in projects of higher-type preservation and functional improvement projects, so the frequencies of those categories are also affected, though to a smaller extent. Replacement and do-nothing win more competitions so their frequencies increase.

Appendix B10 performs the same analysis for functional improvement costs, and Appendix B11 for replacement costs. As replacement costs increase, the frequency of replacement declines dramatically. This is made up by increases in preservation and functional improvement. However, there are many bridges that lack cost-effective preservation candidates, so they are assigned do-nothing instead. As a result, overall condition declines, as do life cycle benefits. In the area of very high replacement costs, the cost curve becomes lumpy as the number of replacement projects becomes very small.

Comparing Appendices B6 through B11, it is possible to gain an impression of relative sensitivity, which implies relative importance of precision in the unit cost estimate. One valid way to compare, is to compute the slope of the life cycle benefit line in the vicinity of the current PLAT unit costs. A way to express this quantitatively is to compute the change in benefit between a doubling and halving of the unit cost. These results are:

100 – Replace element	1148
200 – Rehabilitate	1775
300 – Repair	158
400 – Maintain	4533
500 – Improve	14366
600 – Replace bridge	70205

White cells represent valid sub-categories; numbers refer to footnotes

			Action Category			
		Object	100-Replace	200-Rehab	300-Repair	400-Maint
Materials	0	Other material	▨	▨	▨	1
	1	Deck		2	3	4
	2	Steel/coat (incl metal)	5		6	7
	3	Concrete	▨		8	9
	4	Timber	▨		▨	
	5	Masonry	▨		▨	
	6	MSE	▨		▨	
Hi-Maint	10	Other element	▨	▨	▨	▨
	11	Joint				
	12	Joint seal		▨	▨	▨
	13	Bearing (incl p/h)			▨	
	14	Railing		▨	▨	▨
Drainage	21	Slope prot			▨	▨
	22	Channel	▨		▨	
	23	Drain sys			▨	
Machinery	31	Machinery	10	10	10,11	10
	32	Cath prot		▨	▨	▨
Major	41	Beam		▨	▨	▨
	42	Truss/arch/box		▨	▨	▨
	43	Cable			▨	▨
	44	Substr elem (exc cap)	12	▨	▨	▨
	45	Culvert		▨	▨	▨
	46	Appr slab		13	▨	
Appurtenances	51	Pole/sign		▨	▨	▨

Footnotes

1. Wash structure
2. Rehab deck and replace overlay
3. Repair deck and substrate
4. Repair potholes
5. Replace paint system
6. Spot paint
7. Restore top coat
8. Clean rebar and patch
9. Patch minor spalls
10. Includes electrical, hydraulic, and mechanical elements
11. Repair and lubricate
12. Includes fenders, dolphins, and pile jackets
13. Mudjacking

Figure 2.1. Action categories and sub-categories

It may be surprising to see that maintenance cost variance is the most influential of preservation categories, followed by rehabilitation. One caution to keep in mind is that the PLAT models for maintenance did not receive the same level of detail in their cost analysis, as did the higher action levels. So there is a considerable amount of uncertainty in any results based on the maintenance unit costs.

Functional improvement costs affect only a minority of bridges, but because of their large magnitude they still have an out-sized influence on network-wide economic impacts. Replacement costs, which affect a larger number of bridges and also are larger in magnitude, have a correspondingly larger effect.

2.1.4 Scale feasibility

Scale feasibility determines whether the amount of a particular type of need on a bridge is sufficient to affect the choice of action. This decision is not strictly limited to individual elements, because each bridge could have several elements with the same type of need: for example, girders, floor beams, and stringers may all need to be painted. The scale feasibility model is applied to all actions shown as feasible in Pontis, whether or not the Pontis network optimization finds them to be optimal. There are two feasibility thresholds:

- Maximum – An action sub-category is marked infeasible if the percent in condition states where it would otherwise be feasible, is above a maximum threshold on any given condition unit. A higher-type action, such as replacement, should be considered instead.
- Minimum – For each action sub-category, all the condition units on the bridge that can use it, are grouped together. This is done by computing a weighted average percent in the states where the action is otherwise feasible. Weighting is according to the sum of fixed and variable costs if all the action is applied to the entire condition unit. The action is marked infeasible if the combined percentage is below a minimum threshold. It would be better to wait until the quantity becomes larger, to make the work more economical.

Thresholds are set on the Action Sub-Categories worksheet. The PLAT values are given in Figure 2.2. Since the maximum thresholds are rarely binding, the sensitivity analysis was performed using the minimum thresholds. The results are shown in Appendices B12 and B13. For each of the first 11 cases, the minimum threshold is lowered using the following formula:

$$L_i = L_0 + L_0 F_i \qquad (2.3)$$

where L_i is the new lower threshold
L_0 is the original minimum threshold used in the PLAT
F_i is the sensitivity factor, ranging from -1.0 to -0.1 on a linear scale

A value of -1.0 causes all thresholds to be set to zero, rendering them ineffective. A value of 0.0 indicates no change to the PLAT defaults.

For the final 8 cases, the minimum threshold is raised using the following formula:

$$L_i = L_0 + (H_0 - L_0) F_i \qquad (2.4)$$

where H_0 is the maximum threshold used in the PLAT
F_i is the sensitivity factor, ranging from 0.1 to 0.8 on a linear scale

Using this formula, if the sensitivity factor were 1.0 then the minimum threshold would equal the maximum threshold.

Examining Appendix B12, the effect of raising the threshold is to make fewer preservation projects feasible. Where replacement alternatives are viable, they are more likely to be selected. Otherwise do-nothing is more likely. A steady increase in maintenance projects can also be observed. In part this is because the initial threshold for maintenance is very low.

Appendix B13 addresses the question of whether repair and rehabilitation projects are rare because of their thresholds. This analysis varies only the thresholds in categories 200 and 300, leaving all others constant. It can be seen that the difference is significant within these action categories, but has very little effect on the larger program.

In both analyses, it can be seen that the scale feasibility thresholds affect the type of work performed, but do not have a very large effect on costs, benefits, or resulting conditions.

Action Sub-Category	Action Category	Name	Minimum Threshold	Maximum Threshold
0	0	Do nothing	0	100
101	100	Replace deck	20	100
102	100	Replace paint system	30	100
111	100	Replace joint	20	100
112	100	Replace joint seal	20	100
113	100	Replace bearing	20	100
114	100	Replace railing	25	100
121	100	Replace slope protection	30	100
123	100	Replace drainage system	25	100
131	100	Replace machinery	25	100
132	100	Replace cathodic protection	10	100
141	100	Replace beam	25	50
142	100	Replace truss/arch	25	50
143	100	Replace cable	10	100
144	100	Replace substructure element	25	50
145	100	Replace culvert	50	100
146	100	Replace approach slab	30	100
151	100	Replace pole/sign	25	100
201	200	Rehab deck/replace overlay	10	30
202	200	Rehab steel	20	50
203	200	Rehab concrete	15	50
204	200	Rehab timber	20	30
205	200	Rehab masonry/other	20	50
206	200	Rehab MSE	20	50
211	200	Rehab joint	20	50
213	200	Rehab bearing	10	50
221	200	Rehab slope protection	20	100
222	200	Rehab channel	25	50
223	200	Rehab drainage system	15	50
231	200	Rehab machinery	10	50
243	200	Rehab cable	10	50
246	200	Mudjacking	25	100
301	300	Repair deck and substrate	5	20
302	300	Spot paint	10	30
303	300	Clean rebar and patch	5	20
311	300	Repair joint	10	25
331	300	Repair/lubricate machinery	5	30
400	400	Wash structure	0	75
401	400	Repair potholes	5	25
402	400	Restore top coat	5	10
403	400	Patch minor spalls	5	25
404	400	Maintain timber	10	25
405	400	Maintain masonry	10	25
406	400	Maintain MSE	10	25
411	400	Maintain joint	10	25
413	400	Maintain bearing	5	20
422	400	Maintain channel	5	50
423	400	Maintain drainage system	10	25
431	400	Maintain machinery	5	25
446	400	Maintain approach slab	10	20

Figure 2.2. Scale feasibility thresholds

2.1.5 Paint system replacement

Total recoating projects are quite rare in the data set: only 8 were recommended in the full inventory, and only one of these made it to the sample data set used in the sensitivity analysis. Thus, Appendix B14 does not contain much insight.

The paint system replacement threshold, which is set at 50% in the PLAT, represents the weighted percent of painted steel elements that are in condition state 2 or worse. The weighting is according to paint system replacement cost. As expected, varying this threshold had very little effect on network-wide results. It should be set using expert judgment to yield reasonable project level results.

2.1.6 Deck replacement

Deck replacement in Pontis is a unitary action; that is, it is always applied to the entire condition unit. This means unit costs in dollars per sq.ft. are developed using the entire deck area in the denominator. In Florida decks are the only element handled in this way. Florida does not use winter deicing chemicals and does not experience the same difficult deck maintenance issues common in other states. Pontis deck models optimized with Florida feasible actions, transition probabilities, and costs, tend to let the deck deteriorate to the worst condition state before a do-something action becomes optimal.

When transition probabilities are used for forecasting on a deck element, the predicted fraction in each condition state is interpreted as a probability that the entire deck will be in that state. The scale feasibility model uses these probabilities, so the minimum threshold is taken as the minimum probability that the deck will be in the investigated condition states. In the project level analysis for a given candidate and implementation year, the worst condition state that has a scale-feasible and optimal do-something action determines what action will be scoped for the entire deck.

Whenever the Auto MRR&I Candidate includes a deck replacement scope item, special handling in the model ensures that any additional deck elements, joints, barriers, and drainage systems on the bridge are also replaced. The sensitivity analysis investigated whether this rule has a strong network level effect, by comparing cases where the rule is turned on and off, in Appendix B15. It was found that the effect was quite small, owing to the infrequency of deck replacement projects.

2.1.7 Output quantities and costs

In preservation projects, it is common for the quantity of work in a particular scope item to differ from the quantity in the condition state for which the scope item's action is optimal according to Pontis. The PLAT contains a mechanism to identify, for each element and action category, the condition states to which the action is applicable. It sets the quantity of work based on this broader concept of applicability. It then matches the work to condition states in order to determine the most appropriate unit costs, action effectiveness vectors, and benefits.

The algorithm to do this examines the predicted probabilities in each condition state, starting with the worst. For each state, it examines the scope items (starting with the lowest action sub-category number, generally the most expensive) to find work most appropriate for that state. When it finds a match of actions, it matches quantities, and then deducts the matched quantity from running tallies of quantities in the condition state and scope item. The algorithm works in five stages, performing all possible matches at each stage for all condition states before proceeding to the next, stopping when all quantities of both condition states and scope items have been assigned. The stages are:

1. Optimal – A match occurs if the scope item's action subcategory agrees with the Pontis optimal action for the condition state.
2. Feasible – A match occurs if the scope item's action subcategory agrees with any Pontis feasible action for the condition state.
3. Applicable – A match occurs if the scope item's action subcategory is applicable to the condition state. This search is done by examining other conditions states and their action lists, first in the direction of worse states, then in the direction of better states, until all states are examined or an action is found that matches the scope item's action sub-category and is applicable to the investigated condition state.
4. Non-Applicable – This is similar to the Applicable search except that the match is based only on action sub-category, without requiring that the action be applicable to the investigated condition state. This search occurs only toward states worse than the investigated state.
5. Ineffective – This is similar to the Non-Applicable search, except it starts at state 1. It is effective only for custom candidates, so it does not affect the sensitivity analysis.

For any match in the first four stages, the model uses the matched condition state and action to locate appropriate unit costs, long-term costs (for the benefit calculation), and action effectiveness vectors.

Since the optimal actions have the highest unit benefits for any given condition state, it should be expected that the addition of more condition states (those where the action is feasible or applicable, but not optimal) to a project should lower the average unit benefit of the project. This is because the PLAT does not separate out the effect of indirect costs. If the indirect cost model were separate, the addition of scope to a project would increase the direct cost in proportion to the added quantity, but would make a smaller addition to indirect costs. In that case average life cycle benefits of the project might increase.

The sensitivity analysis progressively added scope to each project in the steps listed above. Appendix B16 shows the results. It can be seen that step 2 makes a significant change to network-wide benefits, lowering them as expected. The added quantity and lowered benefits causes many projects to become unattractive relative to do-nothing, thus decreasing the total number of projects and the total cost. Steps 3 and 4 have a relatively small additional effect, and step 5 has no effect at all, as expected.

The reduction in the number of cost-effective projects in step 2 is probably an undesirable outcome, considering the purpose of the model. It is likely caused by the fact that the PLAT scales indirect costs in direct proportion to direct costs. In reality, the reason work crews add quantity to existing projects, is that the added work can be performed with little or no increase in mobilization, engineering, or maintenance of traffic costs. It would be worth considering an enhancement to this part of the model in a future version of the PLAT.

2.1.8 Effect of uncertainty

A by-product of the sensitivity analysis is a measure of the relative effect of uncertainty in each of the model inputs. This is one part of the decision regarding the level of detail to give to future model refinement. In most of the sensitivity runs, a convenient measure of the effect of uncertainty is the slope of the benefit line in the vicinity of the current input values used in the PLAT. This is approximated by the difference in benefits between doubling and halving the input value. The choice of those particular cases is arbitrary, but still useful since it is available consistently across nearly all of the analyses. Here is a list of these results:

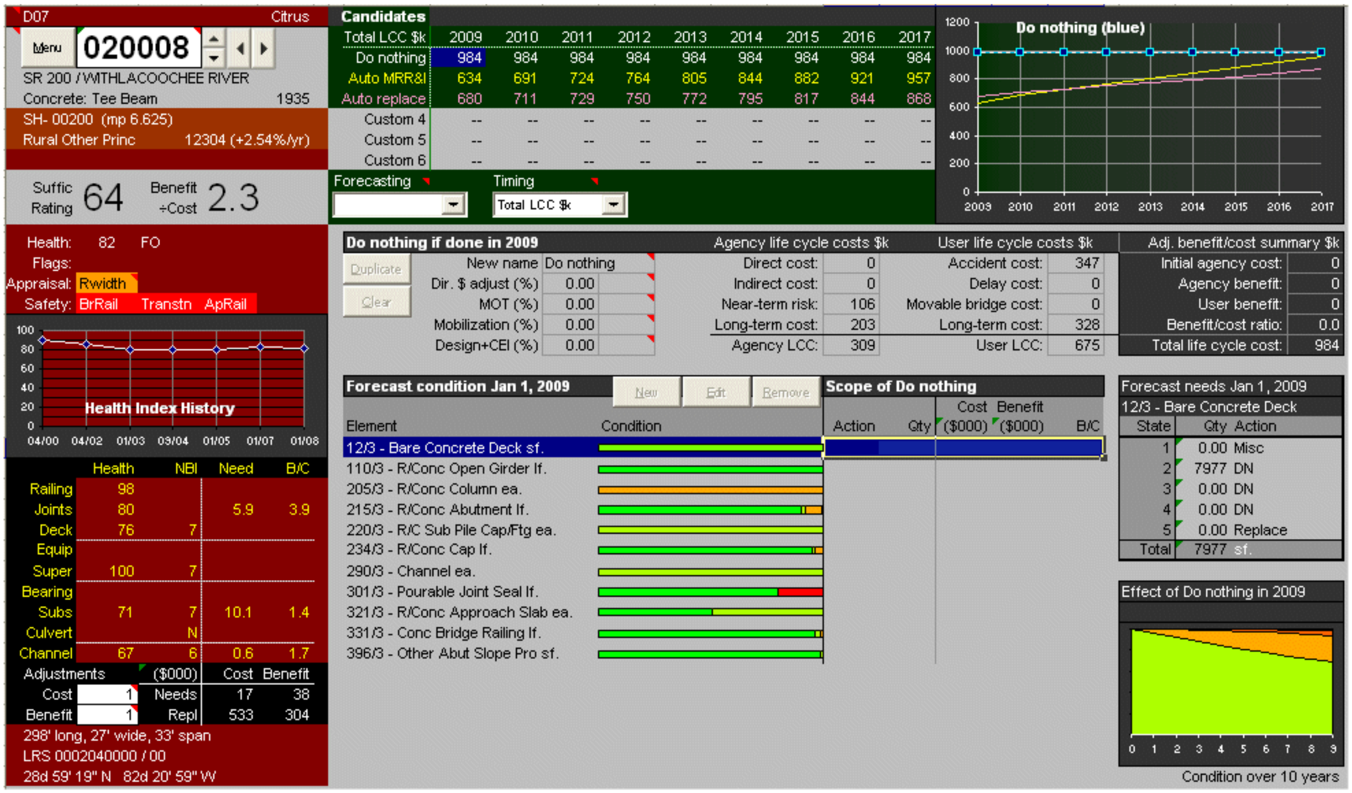
Deterioration model	Appendix B1	13441
Preservation costs	Appendix B5	7448
Improvement costs	Appendix B10	14366
Replacement costs	Appendix B11	70205
Scale feasibility	Appendix B12	515
Output quantity and cost	Appendix B16	6020

Although the uncertainty measure is rough, there is a clear stratification of concerns in the results, with replacement cost in the top tier, and deterioration and improvement cost sharing the second tier. The third tier is shared by preservation costs and the output quantity and cost model.

2.2 Comparison of PLAT/NAT with NCHRP Report 590

Florida’s Project Level Analysis Tool (PLAT) (Sobanjo and Thompson 2004) was developed in 2001-2004 as an add-on to the Pontis bridge management system (Cambridge 2001). Pontis is a product of the American Association of State Highway and Transportation Officials (AASHTO) and used by 46 states. The PLAT’s purpose is to present a more graphical view of current performance and possible futures for a bridge, and to try out new concepts of scoping and cost estimation that might improve the quality of the analytical results and the relevance of the AASHTO product to Florida practice. The user interface concept in the PLAT, known as a digital dashboard, was new to bridge management but proved to be well received nationwide (Figure 2.3). The analysis questions addressed by the project also received increased national attention due to the Florida research.

In 2005-2006 the results of the PLAT analysis were extended to the network level to support programming and budgeting in the Network Analysis Tool (NAT, Figure 2.4) (Sobanjo and Thompson 2007). This uses a second Excel-based digital dashboard for entering budget constraints, and includes tools for convenient graphical presentation of costs and performance for any subset of the bridge inventory. The types of performance information produced by the system include life cycle costs, condition measures (health index and National Bridge Inventory condition ratings), and functional characteristics such as accident risk and truck detours. The software answers a key programming and budgeting question: how much performance can be purchased for given levels of funding, for the entire bridge inventory or any part of it.



D07 Citrus

020008

SR 200 / WITHLACOOCHEE RIVER

Concrete: Tee Beam 1935

SH- 00200 (mp 6.625)

Rural Other Princ 12304 (+2.54%/yr)

Suffic Rating 64

Benefit ÷Cost 2.3

Health: 82 FO

Flags:

Appraisal: Rwidth

Safety: BrRail Transtn ApRail

	Health	NBI	Need	B/C
Railing	98			
Joints	80		5.9	3.9
Deck	76	7		
Equip				
Super	100	7		
Bearing				
Subs	71	7	10.1	1.4
Culvert		N		
Channel	67	6	0.6	1.7

Adjustments		($000)	Cost	Benefit
Cost	1	Needs	17	38
Benefit	1	Repl	533	304

298' long, 27' wide, 33' span

LRS 0002040000 / 00

28d 59' 19" N 82d 20' 59" W

Candidates

Total LCC $k	2009	2010	2011	2012	2013	2014	2015	2016	2017
Do nothing	984	984	984	984	984	984	984	984	984
Auto MRR&I	634	691	724	764	805	844	882	921	957
Auto replace	680	711	729	750	772	795	817	844	868
Custom 4	--	--	--	--	--	--	--	--	--
Custom 5	--	--	--	--	--	--	--	--	--
Custom 6	--	--	--	--	--	--	--	--	--

Forecasting:

Timing: Total LCC $k

Do nothing if done in 2009

		Agency life cycle costs $k		User life cycle costs $k		Adj. benefit/cost summary $k	
New name	Do nothing	Direct cost:	0	Accident cost:	347	Initial agency cost:	0
Dir. $ adjust (%)	0.00	Indirect cost:	0	Delay cost:	0	Agency benefit:	0
MOT (%)	0.00	Near-term risk:	106	Movable bridge cost:	0	User benefit:	0
Mobilization (%)	0.00	Long-term cost:	203	Long-term cost:	328	Benefit/cost ratio:	0.0
Design+CEI (%)	0.00	Agency LCC:	309	User LCC:	675	Total life cycle cost:	984

Forecast condition Jan 1, 2009

Scope of Do nothing

Element	Condition	Action	Qty	Cost ($000)	Benefit ($000)	B/C
12/3 - Bare Concrete Deck sf.						
110/3 - R/Conc Open Girder lf.						
205/3 - R/Conc Column ea.						
215/3 - R/Conc Abutment lf.						
220/3 - R/C Sub Pile Cap/Ftg ea.						
234/3 - R/Conc Cap lf.						
290/3 - Channel ea.						
301/3 - Pourable Joint Seal lf.						
321/3 - R/Conc Approach Slab ea.						
331/3 - Conc Bridge Railing lf.						
396/3 - Other Abut Slope Pro sf.						

Forecast needs Jan 1, 2009

12/3 - Bare Concrete Deck

State	Qty	Action
1	0.00	Misc
2	7977	DN
3	0.00	DN
4	0.00	DN
5	0.00	Replace
Total	7977	sf.

Figure 2.3. Florida Project Level Analysis Tool (PLAT)

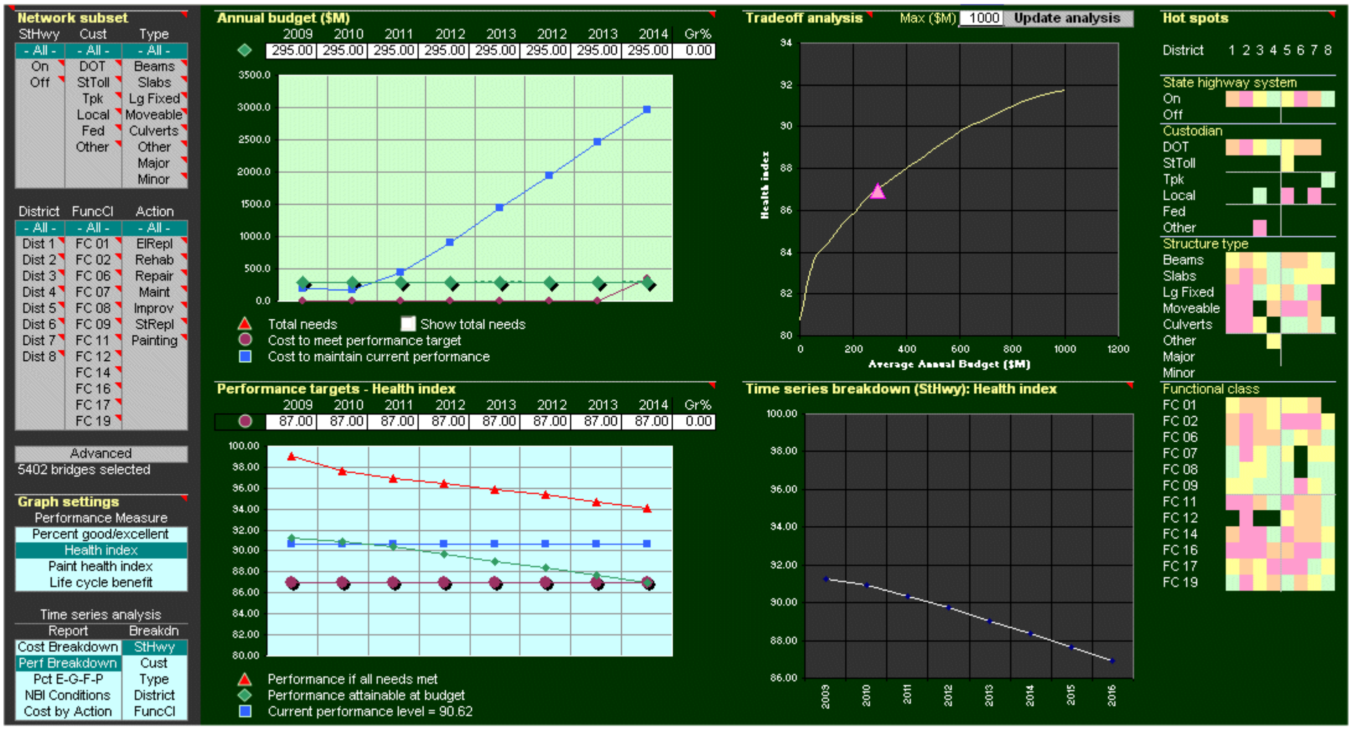
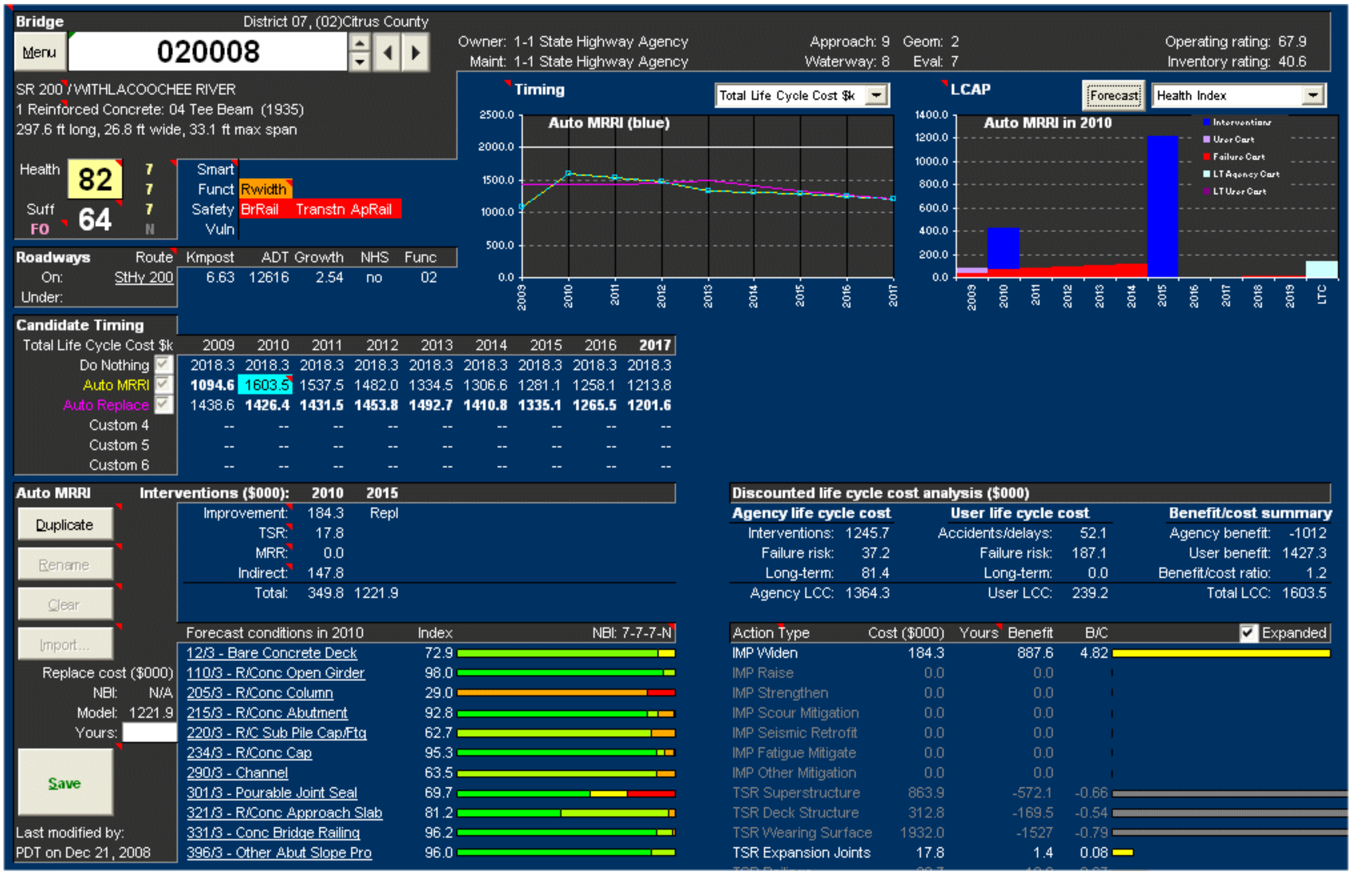


Figure 2.4. Florida Network Analysis Tool (NAT)

While the optimization mechanism in the NAT is very similar to Pontis, the system architecture of PLAT/NAT broke new ground. Instead of embedding the bridge level analysis in a larger network-wide simulation model, as is done in Pontis, PLAT/NAT stores bridge level results in an intermediate database. This gives the user much more opportunity to develop customized project definitions over the course of the year. NAT reads from the database whatever PLAT results are available at the time, and is thus able to present its results much more quickly (seconds rather than hours), and is instantly responsive to changes in budget levels.

In 2004-2007, National Cooperative Highway Research Program (NCHRP) Project 12-67 explored a separate problem in bridge management, the criteria used for priority setting and resource allocation. The researchers developed a framework, based on utility theory, to give more weight to condition and vulnerability than would be possible in Pontis or the PLAT. By removing the Pontis analysis from the constraints of a purely economic life cycle cost framework, the new models would be able to more accurately reflect public attitudes toward risk, community image, and externalities, all factors where decision makers often do not trust economic quantification.



Bridge District 07, (02)Citrus County

020008

SR 200 / WITHLACOOCHEE RIVER
1 Reinforced Concrete: 04 Tee Beam (1935)
297.6 ft long, 26.8 ft wide, 33.1 ft max span

Owner: 1-1 State Highway Agency
Maint: 1-1 State Highway Agency
Approach: 9 Geom: 2
Waterway: 8 Eval: 7
Operating rating: 67.9
Inventory rating: 40.6

Health 82 7
7
Suff 64 7
FO N

Smart
Funct Rwidth
Safety BrRail Transtn ApRail
Vuln

Roadways	Route	Kmpost	ADT	Growth	NHS	Func
On:	StHy 200	6.63	12616	2.54	no	02
Under:						

Candidate Timing

Total Life Cycle Cost $k		2009	2010	2011	2012	2013	2014	2015	2016	**2017**
Do Nothing	☑	2018.3	2018.3	2018.3	2018.3	2018.3	2018.3	2018.3	2018.3	2018.3
Auto MRRI	☑	**1094.6**	1603.5	1537.5	1482.0	1334.5	1306.6	1281.1	1258.1	1213.8
Auto Replace	☑	1438.6	**1426.4**	**1431.5**	**1453.8**	**1492.7**	**1410.8**	**1335.1**	**1265.5**	**1201.6**
Custom 4		--	--	--	--	--	--	--	--	--
Custom 5		--	--	--	--	--	--	--	--	--
Custom 6		--	--	--	--	--	--	--	--	--

Auto MRRI

Interventions ($000):	2010	2015
Improvement:	184.3	Repl
TSR:	17.8	
MRR:	0.0	
Indirect:	147.8	
Total:	349.8	1221.9

Replace cost ($000)
NBI: N/A
Model: 1221.9
Yours:

Last modified by:
PDT on Dec 21, 2008

Forecast conditions in 2010	Index
12/3 - Bare Concrete Deck	72.9
110/3 - R/Conc Open Girder	98.0
205/3 - R/Conc Column	29.0
215/3 - R/Conc Abutment	92.8
220/3 - R/C Sub Pile Cap/Ftg	62.7
234/3 - R/Conc Cap	95.3
290/3 - Channel	63.5
301/3 - Pourable Joint Seal	69.7
321/3 - R/Conc Approach Slab	81.2
331/3 - Conc Bridge Railing	96.2
396/3 - Other Abut Slope Pro	96.0

NBI: 7-7-7-N

Discounted life cycle cost analysis ($000)

Agency life cycle cost		**User life cycle cost**		**Benefit/cost summary**	
Interventions:	1245.7	Accidents/delays:	52.1	Agency benefit:	-1012
Failure risk:	37.2	Failure risk:	187.1	User benefit:	1427.3
Long-term:	81.4	Long-term:	0.0	Benefit/cost ratio:	1.2
Agency LCC:	1364.3	User LCC:	239.2	Total LCC:	1603.5

☑ Expanded

Action Type	Cost ($000)	Yours	Benefit	B/C
IMP Widen	184.3		887.6	4.82
IMP Raise	0.0		0.0	
IMP Strengthen	0.0		0.0	
IMP Scour Mitigation	0.0		0.0	
IMP Seismic Retrofit	0.0		0.0	
IMP Fatigue Mitigate	0.0		0.0	
IMP Other Mitigation	0.0		0.0	
TSR Superstructure	863.9		-572.1	-0.66
TSR Deck Structure	312.8		-169.5	-0.54
TSR Wearing Surface	1932.0		-1527	-0.79
TSR Expansion Joints	17.8		1.4	0.08

Figure 2.5. NCHRP 590 Bridge Level Dashboard

The products of NCHRP Project 12-67 were published in Report 590 (Patidar et al. 2007). This report includes a software system developed to demonstrate the multi-objective concept using Pontis data. This product is called the Multi-Objective Optimization System (MOOS). Like PLAT/NAT, the software consists of two Excel workbook files — bridge level and network level — connected by an intermediate Access database. The bridge level user interface (Figure 2.5) was strongly influenced by the Florida PLAT software for its dashboard presentation, although the underlying analysis turned out to be much different because of the multi-objective framework and the possibility of multiple interventions over a longer analysis period. The Report 590 software addressed some of the same project scoping issues raised by the PLAT, but used a different approach for its solution.

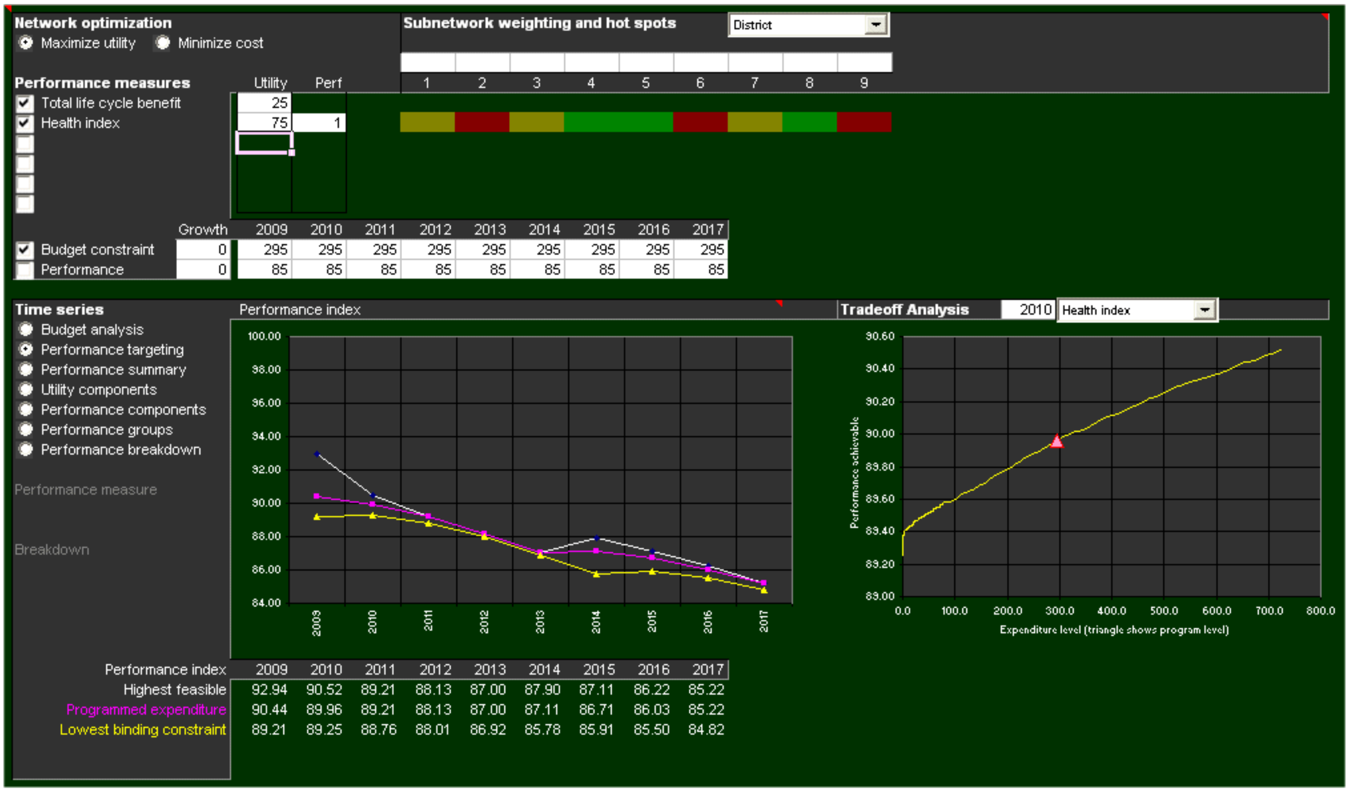
The network level model in Report 590 (Figure 2.6) was again strongly influenced by the Florida work in the way it presents time series of cost and performance results, and expresses cost versus performance tradeoffs. However it is specialized for working with relative weights of performance criteria in the utility function, and for defining dual constraints on budget and performance. Because of the possibility of a performance constraint, a different optimization algorithm was needed in the Report 590 product.

While PLAT/NAT was developed specifically to fit Florida needs, the relevance to other bridge owners was obvious at the time of NCHRP Report 590 development. Early in the Report 590 study, one question that was investigated was whether any of the Florida software could be re-used to save money in the NCHRP project. This turned out to be impossible, due to differences in project objectives and requirements, which caused major differences in the underlying models.

However, the NCHRP project did use the best architectural and user interface concepts proven by PLAT/NAT, thus allowing the NCHRP research to explore much further into the multi-objective concept than might otherwise be possible.

In a similar manner, both the Florida and NCHRP projects are highly influential in the design of the next major version of AASHTO’s Pontis, release 5.2. This is an excellent example of Florida DOT research that has an immediate impact on outside research, and through the combined effort is able to be implemented nationwide in a relatively short time.

Because of the architectural similarities between PLAT/NAT and NCHRP 590, and the fact that they serve similar purposes and share a common database, there are several useful points of comparison that can help to evaluate the relative effectiveness of the different sub-models and point to future improvements. This memorandum explores those comparisons.



Network optimization

● Maximize utility ○ Minimize cost

Subnetwork weighting and hot spots District

1	2	3	4	5	6	7	8	9
🟨	🟥	🟨	🟩	🟩	🟥	🟨	🟩	🟥

Performance measures	Utility	Perf
☑ Total life cycle benefit	25	
☑ Health index	75	1
☐		
☐		
☐		
☐		

	Growth	2009	2010	2011	2012	2013	2014	2015	2016	2017
☑ Budget constraint	0	295	295	295	295	295	295	295	295	295
☐ Performance	0	85	85	85	85	85	85	85	85	85

Time series

○ Budget analysis
● Performance targeting
○ Performance summary
○ Utility components
○ Performance components
○ Performance groups
○ Performance breakdown

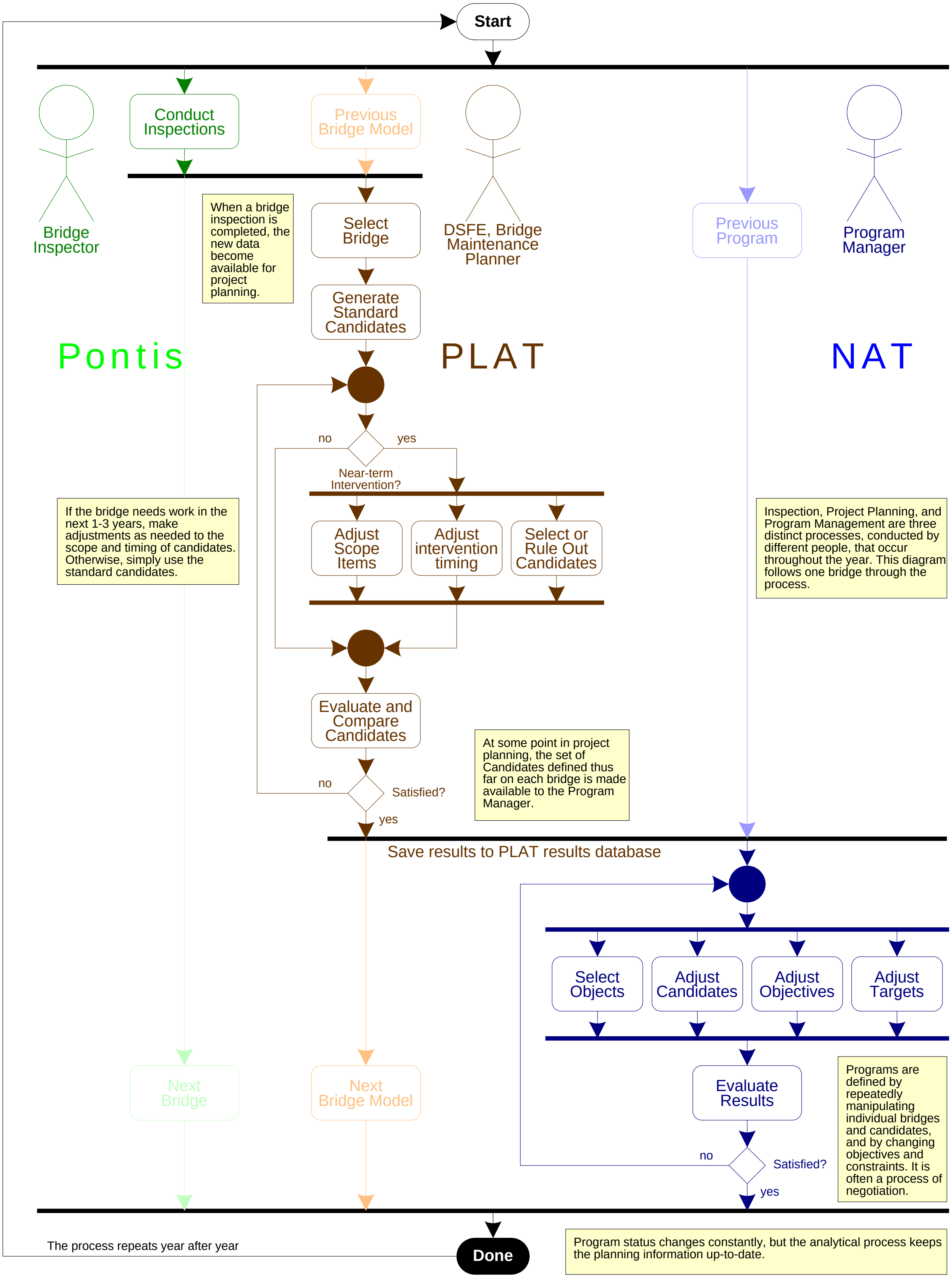
Performance measure

Breakdown

Tradeoff Analysis 2010 Health index

Performance index	2009	2010	2011	2012	2013	2014	2015	2016	2017
Highest feasible	92.94	90.52	89.21	88.13	87.00	87.90	87.11	86.22	85.22
Programmed expenditure	90.44	89.96	89.21	88.13	87.00	87.11	86.71	86.03	85.22
Lowest binding constraint	89.21	89.25	88.76	88.01	86.92	85.78	85.91	85.50	84.82

Figure 2.6. NCHRP 590 Network Level Dashboard



When a bridge inspection is completed, the new data become available for project planning.

If the bridge needs work in the next 1-3 years, make adjustments as needed to the scope and timing of candidates. Otherwise, simply use the standard candidates.

Inspection, Project Planning, and Program Management are three distinct processes, conducted by different people, that occur throughout the year. This diagram follows one bridge through the process.

At some point in project planning, the set of Candidates defined thus far on each bridge is made available to the Program Manager.

Programs are defined by repeatedly manipulating individual bridges and candidates, and by changing objectives and constraints. It is often a process of negotiation.

Program status changes constantly, but the analytical process keeps the planning information up-to-date.

Figure 2.7. Business process model for PLAT/NAT

2.2.1 Overview of the two systems and points of comparison

PLAT and NAT work together with Pontis to support two related business processes of the Department, as shown schematically in Figure 2.7 (from the Florida NAT Users Manual). Bridge inspections are conducted on a 2-year cycle and stored in the Pontis database. The PLAT uses this information on a 1-year cycle, mostly in the district offices, to decide on the scope and timing of work needed on each bridge. These results are stored in the PLAT Results database. On a separate 1-year cycle, bridge level needs are collected statewide from the PLAT Results database for priority-setting and budgeting.

MOOS is designed for a similar business model, though made much more generic to fit the needs of the full range of centralized and decentralized Departments of Transportation. Report 590 and PLAT/NAT share a similar system architecture, as shown in Figure 2.8 (from the MOOS Users Manual). The bridge level model in both cases is designed for a high level of user interaction to set the scope and timing of projects. Both systems also have a "batch process" that can analyze the entire inventory without user intervention, to populate their intermediate databases.

In both cases, this batch analysis takes about 20 minutes for the full database of 6,529 FDOT bridges, when the two systems are configured to perform a 9-year analysis (using 2008-vintage Windows-based computers). MOOS is also capable of performing longer analyses, up to 30 years, with multiple interventions on the same bridge. This can extend the amount of time required to complete an analysis to as many as 5 hours.

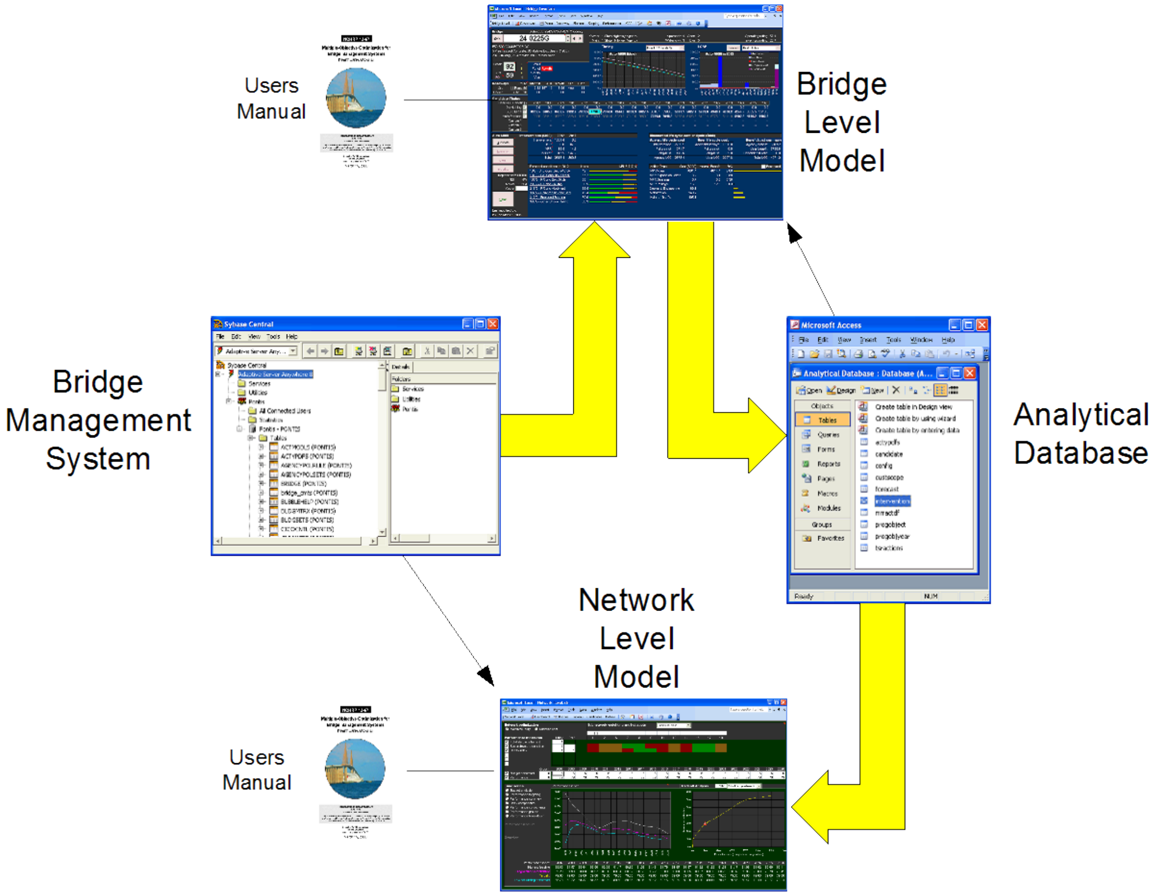


Figure 2.8. MOOS system architecture, also applicable to PLAT/NAT

2.2.2 Life cycle activity profiles

Figure 2.9, from the MOOS users manual, presents the life cycle activity framework. Life cycle costs consist of several components:

- Initial costs of interventions, divided into direct and indirect costs. Indirect costs consist of mobilization, maintenance of traffic, and engineering.
- Long-term costs, which are an estimate of intervention costs which might occur beyond the end of the program horizon.
- User costs, including time, fuel, repair, and accident costs due to functional deficiencies of bridges. These have near-term and long-term models.
- Failure risk costs, an estimate of unprogrammed costs due to allowing bridge elements to remain in their worst condition state without being repaired. Such costs include agency costs of emergency repair, and user costs of the inconvenience caused by restricting or closing a structure.

In the PLAT, all of these costs are combined, using present value analysis, into life cycle cost, which is the main performance measure. In the MOOS, the main performance measure is utility, a non-economic combination of performance measures which may include life cycle cost but also includes risk, condition, delay, and other variables. PLAT has a simpler variation of the life cycle activity profile shown in Figure 2.9, because it is limited to a 9-year analysis period and does not allow more than one intervention on a bridge during that period.

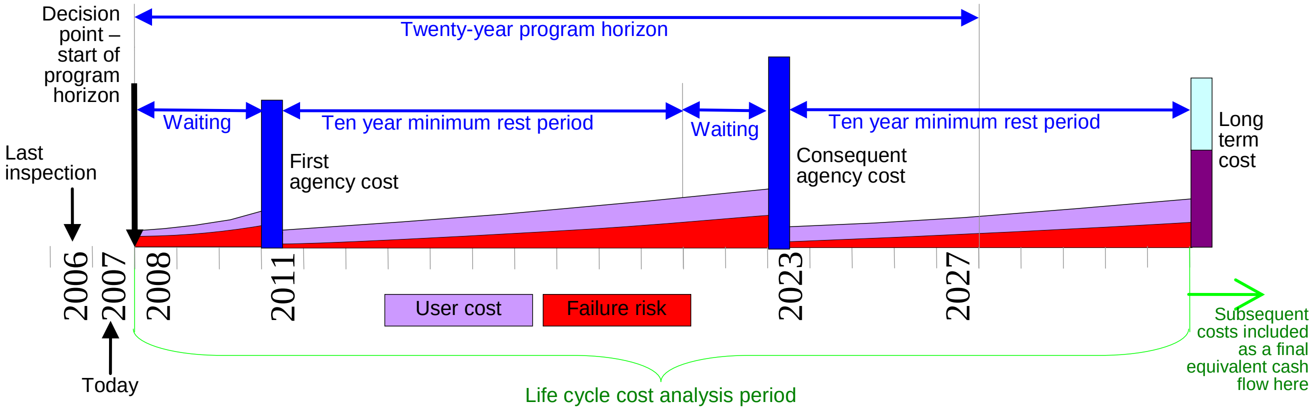


Figure 2.9. Life cycle activity profile

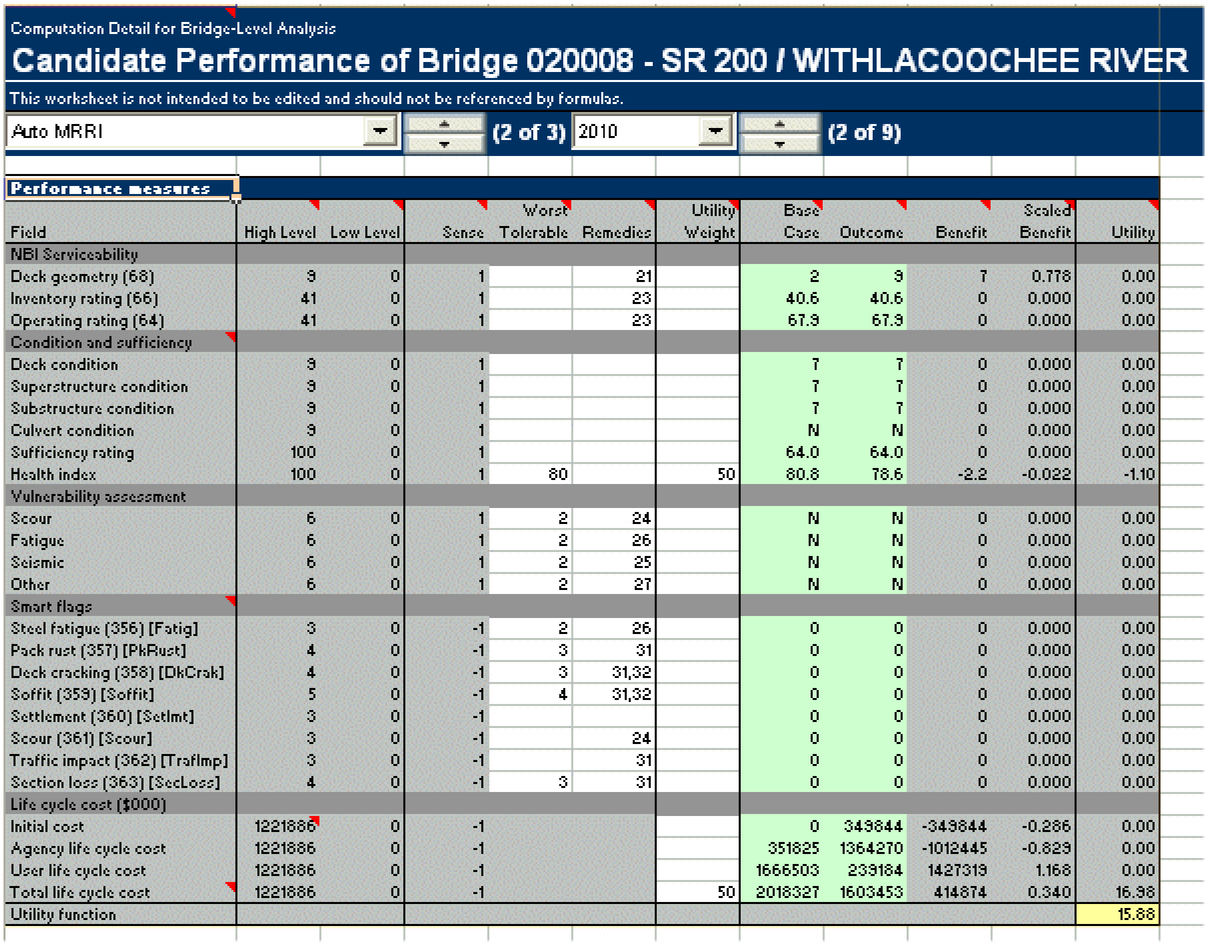
2.2.3 Optimization

In keeping with the similar architectures, both PLAT and MOOS deliver a set of evaluated alternatives for each bridge to the intermediate database. This means that neither system conducts a full optimization at the bridge level, though both can identify the best scope and timing of work according to their respective performance measures.

Both systems rely on a network level model to select from among competing alternatives. When funding is plentiful, both network optimization models tend to select more expensive projects, such as replacement, that have higher benefits. When funding is tight, both will tend to select smaller projects, such as repairs, and will also push projects farther into the future.

At the bridge level, the PLAT generally stores every possible combination of scope and timing of work in the intermediate database, thus relying completely on the NAT for optimization. As will be noted later in this memorandum, the PLAT/NAT architecture gives the user a great deal of flexibility to generate a wide range of alternative network-level programs, and is very responsive to changes in inputs.

MOOS, on the other hand, has two procedures for bridge level optimization, whose effect is to narrow the list of alternatives made available to the network level. MOOS ranks alternatives by incremental utility/cost ratio and eliminates alternatives that are unattractive by this measure. It also allows the user to set performance criteria that must be satisfied in order for actions to be triggered. Figure 2.10 shows the worksheet for configuring performance measures.



Computation Detail for Bridge-Level Analysis

Candidate Performance of Bridge 020008 - SR 200 / WITHLACOOCHEE RIVER

This worksheet is not intended to be edited and should not be referenced by formulas.

Auto MRRI (2 of 3) 2010 (2 of 9)

Performance measures

Field	High Level	Low Level	Sense	Worst Tolerable	Remedies	Utility Weight	Base Case	Outcome	Benefit	Scaled Benefit	Utility
NBI Serviceability											
Deck geometry (68)	9	0	1		21		2	9	7	0.778	0.00
Inventory rating (66)	41	0	1		23		40.6	40.6	0	0.000	0.00
Operating rating (64)	41	0	1		23		67.9	67.9	0	0.000	0.00
Condition and sufficiency											
Deck condition	9	0	1				7	7	0	0.000	0.00
Superstructure condition	9	0	1				7	7	0	0.000	0.00
Substructure condition	9	0	1				7	7	0	0.000	0.00
Culvert condition	9	0	1				N	N	0	0.000	0.00
Sufficiency rating	100	0	1				64.0	64.0	0	0.000	0.00
Health index	100	0	1	80		50	80.8	78.6	-2.2	-0.022	-1.10
Vulnerability assessment											
Scour	6	0	1	2	24		N	N	0	0.000	0.00
Fatigue	6	0	1	2	26		N	N	0	0.000	0.00
Seismic	6	0	1	2	25		N	N	0	0.000	0.00
Other	6	0	1	2	27		N	N	0	0.000	0.00
Smart flags											
Steel fatigue (356) [Fatig]	3	0	-1	2	26		0	0	0	0.000	0.00
Pack rust (357) [PkRust]	4	0	-1	3	31		0	0	0	0.000	0.00
Deck cracking (358) [DkCrak]	4	0	-1	3	31,32		0	0	0	0.000	0.00
Soffit (359) [Soffit]	5	0	-1	4	31,32		0	0	0	0.000	0.00
Settlement (360) [Setlmt]	3	0	-1				0	0	0	0.000	0.00
Scour (361) [Scour]	3	0	-1		24		0	0	0	0.000	0.00
Traffic impact (362) [TrafImp]	3	0	-1		31		0	0	0	0.000	0.00
Section loss (363) [SecLoss]	4	0	-1	3	31		0	0	0	0.000	0.00
Life cycle cost ($000)											
Initial cost	1221886	0	-1				0	349844	-349844	-0.286	0.00
Agency life cycle cost	1221886	0	-1				351825	1364270	-1012445	-0.829	0.00
User life cycle cost	1221886	0	-1				1666503	239184	1427319	1.168	0.00
Total life cycle cost	1221886	0	-1			50	2018327	1603453	414874	0.340	16.98
Utility function											15.88

Figure 2.10. Configuring performance measures in MOOS

At the network level, both systems have a benefit/cost framework that relies on the concept of diminishing marginal returns (Figure 2.11). Both optimizations use a gradient method to try to allocate funding to expenditures that optimize their performance measures: for NAT, this is minimization of life cycle cost, while for MOOS it is maximization of utility.

But the two models differ in the way they apply constraints, leading to different algorithms. NAT, having only a budget constraint, uses an incremental benefit/cost algorithm that is very similar to the one used in Pontis. MOOS has both a budget constraint and a performance constraint, so it uses a more complex (and hence more time-consuming) algorithm. It is because of the greater network level complexity that MOOS performs part of the optimization at the bridge level and

sends fewer alternatives upward. But the downside is that the network level has less flexibility and thus is less able to respond to changes in inputs.
For purposes of the analysis reported here, MOOS was configured to do as little screening as possible at the bridge level, to make it most consistent with PLAT.

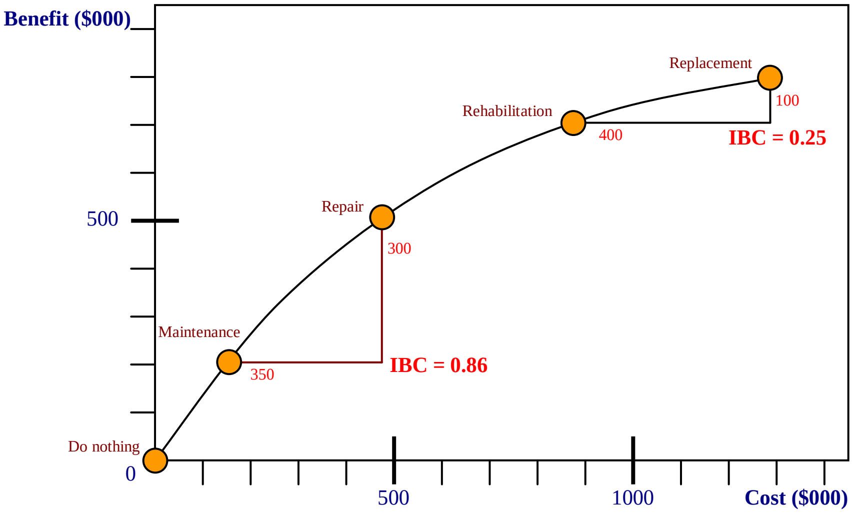


Figure 2.11. Diminishing marginal returns

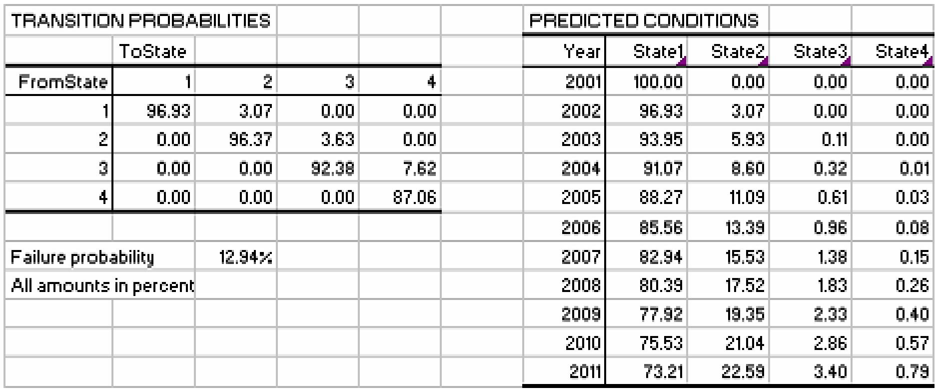
2.2.4 Deterioration and action effectiveness

Both PLAT and MOOS use the same deterioration model (Figure 2.12) and the same action effectiveness model, the only places where the computations in the two systems are nearly the same. These models use Markovian transition probability matrices which are provided in the Pontis database. Both bridge level dashboards use the same graphic conventions for expressing the results of deterioration, shown in Figure 2.13. This is the one place where both systems almost always produce identical results.

PLAT is designed to begin its analysis at the time of the most recent inspection, and to deteriorate conditions to the beginning of the program period, which is usually the year after the computer’s system date. In MOOS this feature is optional, but for this study was activated for consistency with PLAT.

One feature that exists in PLAT but not in MOOS is a model to describe the effect of protective systems on the deterioration rate of underlying elements. The specific protective elements that are modeled are expansion joints and drainage systems. When a protective element is in deteriorated condition, the environment classification of underlying elements is moved to the next more severe grade, causing it to deteriorate faster. If the protective element is in new condition, the protected elements are moved toward a more benign environment by one grade.

This innovation was found to have a noticeable effect on the benefits of repair projects for bridges having deteriorated joints, a common problem in Florida. While MOOS does not have this feature, Pontis 5.2 is expected to pursue the concept using a “protection factor” to represent the combined effect of protective elements, paint systems, wearing surfaces, cathodic protection, washing, and other features and actions that influence deterioration rates.



TRANSITION PROBABILITIES

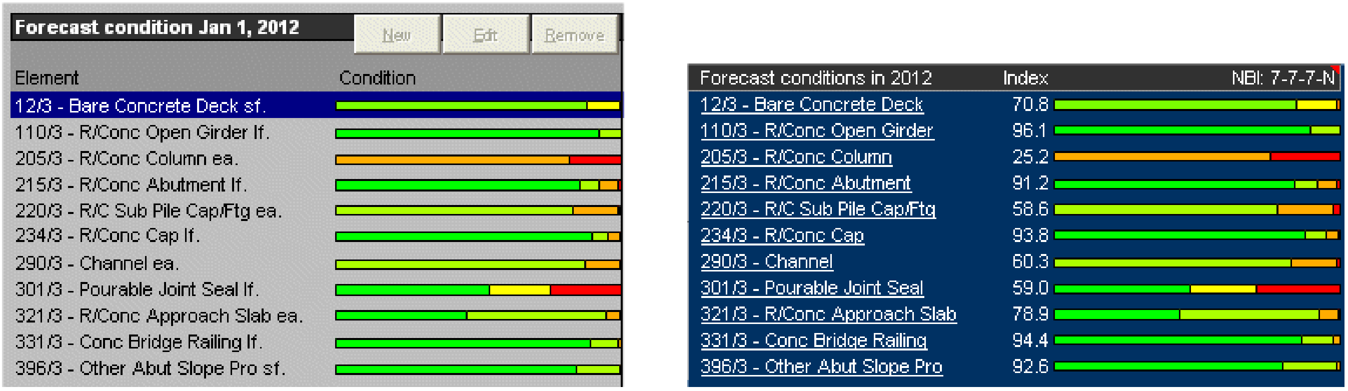
FromState \ ToState	1	2	3	4
1	96.93	3.07	0.00	0.00
2	0.00	96.37	3.63	0.00
3	0.00	0.00	92.38	7.62
4	0.00	0.00	0.00	87.06

Failure probability 12.94%
All amounts in percent

PREDICTED CONDITIONS

Year	State1	State2	State3	State4
2001	100.00	0.00	0.00	0.00
2002	96.93	3.07	0.00	0.00
2003	93.95	5.93	0.11	0.00
2004	91.07	8.60	0.32	0.01
2005	88.27	11.09	0.61	0.03
2006	85.56	13.39	0.96	0.08
2007	82.94	15.53	1.38	0.15
2008	80.39	17.52	1.83	0.26
2009	77.92	19.35	2.33	0.40
2010	75.53	21.04	2.86	0.57
2011	73.21	22.59	3.40	0.79

Figure 2.12. Example of a Markovian deterioration model



Forecast condition Jan 1, 2012

Element	Condition
12/3 - Bare Concrete Deck sf.	
110/3 - R/Conc Open Girder lf.	
205/3 - R/Conc Column ea.	
215/3 - R/Conc Abutment lf.	
220/3 - R/C Sub Pile Cap/Ftg ea.	
234/3 - R/Conc Cap lf.	
290/3 - Channel ea.	
301/3 - Pourable Joint Seal lf.	
321/3 - R/Conc Approach Slab ea.	
331/3 - Conc Bridge Railing lf.	
396/3 - Other Abut Slope Pro sf.	

Forecast conditions in 2012	Index	NBI: 7-7-7-N
12/3 - Bare Concrete Deck	70.8	
110/3 - R/Conc Open Girder	96.1	
205/3 - R/Conc Column	25.2	
215/3 - R/Conc Abutment	91.2	
220/3 - R/C Sub Pile Cap/Ftg	58.6	
234/3 - R/Conc Cap	93.8	
290/3 - Channel	60.3	
301/3 - Pourable Joint Seal	59.0	
321/3 - R/Conc Approach Slab	78.9	
331/3 - Conc Bridge Railing	94.4	
396/3 - Other Abut Slope Pro	92.6	

Figure 2.13. Comparison of PLAT (left) and MOOS depictions of forecast condition

2.2.5 Cost estimation

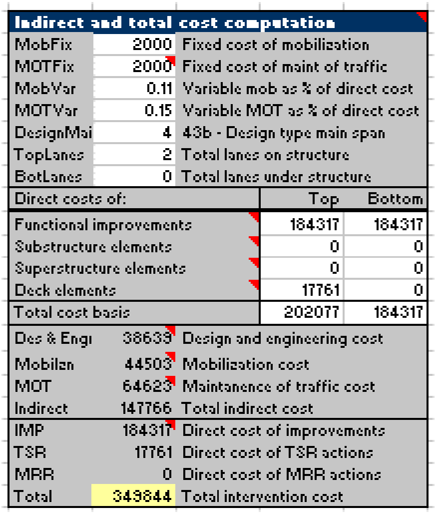
While both PLAT and MOOS obtain their preservation unit costs from the Pontis database, they differ in their methods for functional improvements, replacement, and indirect costs.

For functional improvements and replacement, MOOS relies on the Pontis cost matrix, the same database table that Pontis itself uses. This table provides a separate unit cost for every combination of district, functional class, on/off the National Highway System, and on/off the State highway system.

Indirect costs in MOOS are based on fixed project costs for mobilization and maintenance of traffic (MOT), plus a variable portion which is a constant percentage of direct costs. MOT fixed costs are sensitive to the number of lanes affected by the work. Elements are associated with work on or under the bridge in order to determine the number of lanes affected. Figure 2.14 shows an example calculation.

In PLAT, functional improvement and replacement unit costs are specified within the Excel file and not taken from the Pontis database. These costs do not vary by functional class or jurisdiction. However, replacement costs vary by maximum span length. Indirect costs are specified as constant percentages of direct costs, and vary by type of work. Figure 2.15 shows the cost parameters.

These models are very different from each other. The most important difference is the fixed indirect cost in MOOS, which has the effect of postponing very small maintenance actions because of their relatively high costs for mobilization and MOT.
Because of the importance of movable bridges in Florida, PLAT contains a replacement model for movable bridges, which MOOS does not.

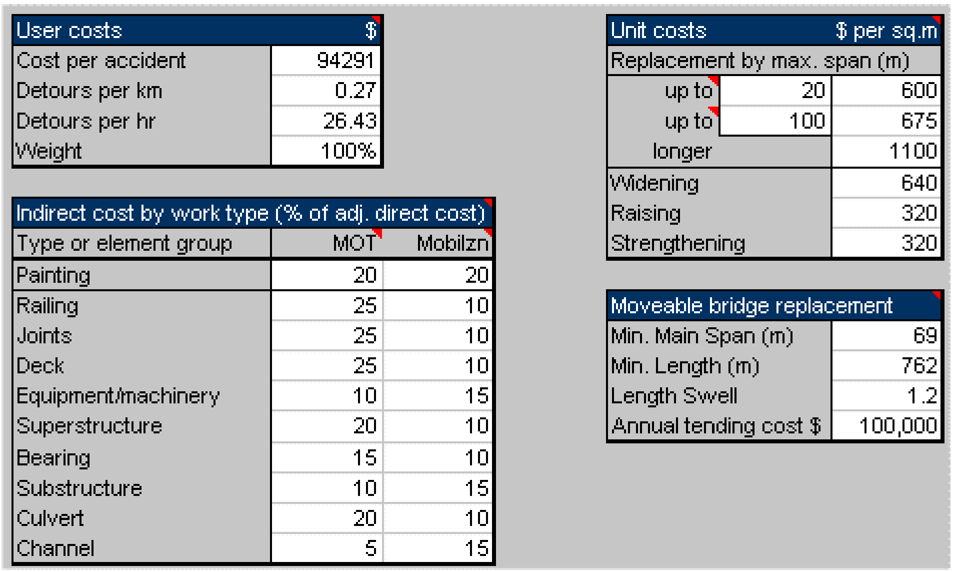


Indirect and total cost computation		
MobFix	2000	Fixed cost of mobilization
MOTFix	2000	Fixed cost of maint of traffic
MobVar	0.11	Variable mob as % of direct cost
MOTVar	0.15	Variable MOT as % of direct cost
DesignMai	4	43b - Design type main span
TopLanes	2	Total lanes on structure
BotLanes	0	Total lanes under structure

Direct costs of:	Top	Bottom
Functional improvements	184317	184317
Substructure elements	0	0
Superstructure elements	0	0
Deck elements	17761	0
Total cost basis	202077	184317

Des & Engi	38639	Design and engineering cost
Mobilzn	44503	Mobilization cost
MOT	64623	Maintanence of traffic cost
Indirect	147766	Total indirect cost
IMP	184317	Direct cost of improvements
TSR	17761	Direct cost of TSR actions
MRR	0	Direct cost of MRR actions
Total	349844	Total intervention cost

Figure 2.14. Example of indirect cost calculation in MOOS



User costs	$
Cost per accident	94291
Detours per km	0.27
Detours per hr	26.43
Weight	100%

Indirect cost by work type (% of adj. direct cost)		
Type or element group	MOT	Mobilzn
Painting	20	20
Railing	25	10
Joints	25	10
Deck	25	10
Equipment/machinery	10	15
Superstructure	20	10
Bearing	15	10
Substructure	10	15
Culvert	20	10
Channel	5	15

Unit costs		$ per sq.m
Replacement by max. span (m)		
up to	20	600
up to	100	675
longer		1100
Widening		640
Raising		320
Strengthening		320

Moveable bridge replacement	
Min. Main Span (m)	69
Min. Length (m)	762
Length Swell	1.2
Annual tending cost $	100,000

Figure 2.15. Cost parameters in PLAT

2.2.6 Failure costs

Pontis in its analytical framework has the concept of a failure state for each element, a state where deterioration is so advanced that functionality of the element is reduced. The Pontis database provides failure unit costs and failure probabilities for the worst condition state of every element. Failure costs in Pontis must be high enough that its network optimization, which minimizes life cycle costs, prefers taking action rather than doing nothing (Thompson 2003). Both MOOS and PLAT use the failure concept at the project level, as a life cycle cost penalty for allowing any portion of an element to remain in the worst state without correcting it.

In MOOS, the failure calculation is a straight forward computation: multiply the quantity in the worst condition state each year by the failure probability and failure cost. Compute the discounted sum of these costs over the analysis period to get total life cycle cost of element failure risk. With this formulation and the typical failure cost data in the Florida Pontis database, failure costs play a very significant role in the model. Figure 2.16 shows a common example of the relative role of failure costs in a life cycle activity profile. MOOS allows the failure cost feature to be turned off, but then it is necessary to use an alternative mechanism to make sure the system doesn't simply recommend doing nothing. In MOOS, the alternatives are to set bridge level or network level condition constraints, or to include a sufficient weight for condition in the utility function, which is maximized.

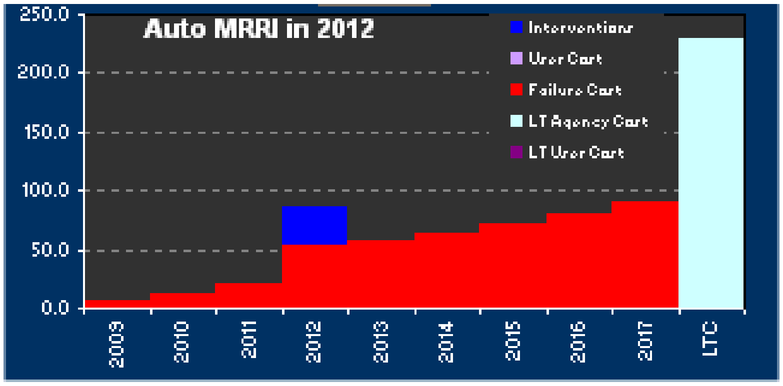


Figure 2.16. Typical life cycle activity profile showing prominent failure costs

In the PLAT, failure cost is given a much less prominent role by recognizing it only in the first year in which element failure is a possibility for some fraction of each element. Once the failure risk is recognized for some portion of an element, this portion is set aside and does not participate in the failure risk for subsequent years. It was found in the present study that this smaller involvement of failure risk was still sufficient to generate realistic programs of projects using the NAT.

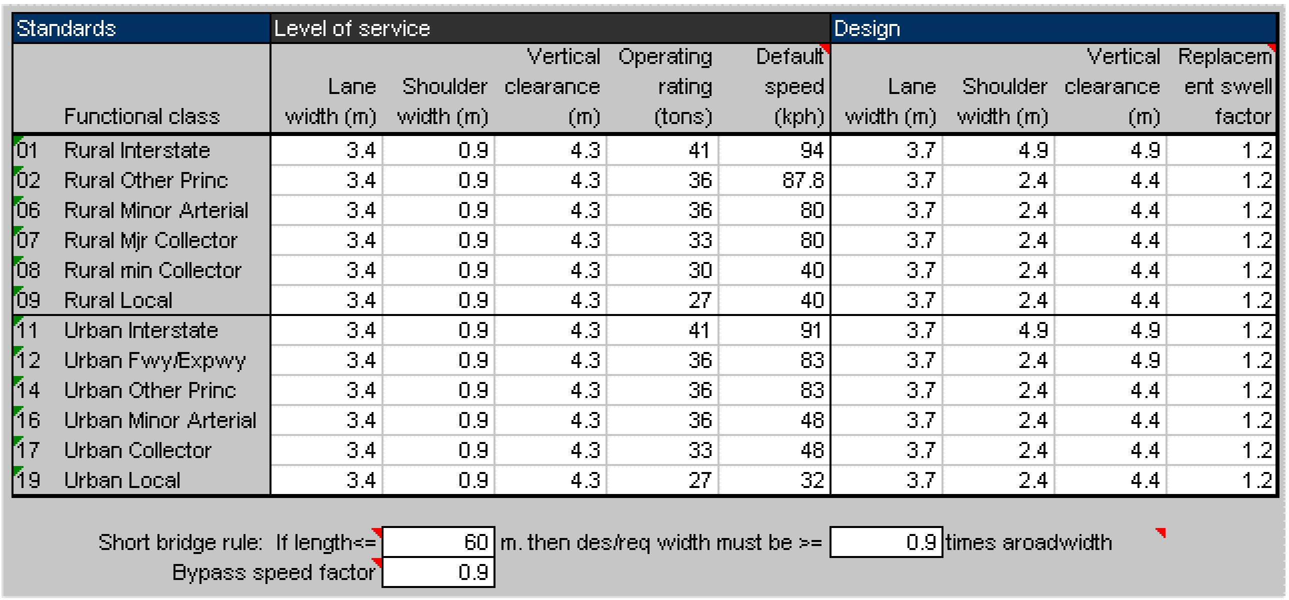
Comparing the MOOS and PLAT approaches to failure risk, the MOOS approach tends to produce a far greater number of repair and rehabilitation projects, as compared to bridge replacement. For example, in one typical matched set of models, PLAT produced 596 MR&R projects, while MOOS produced 2999. When this was explored in more depth by comparing alternative programs in MOOS and PLAT/NAT, it was found that the reason for the difference is the much higher benefit assigned to repairs and rehabilitation in the MOOS framework, with the difference reflecting primarily a savings in failure risk costs. When the MOOS failure cost model was disabled, and replaced by a 75% contribution of health index in the utility function, the number of MR&R projects was reduced to 1290. Of all the inputs to the two systems, the one accounting for the greatest difference between the two frameworks was the failure cost.

This conclusion is interesting because it has been noted in previous studies that the Pontis network optimization model is not very sensitive to failure costs. Where failure costs make a much bigger difference is at the project level, where there is an explicit tradeoff between spot repairs, versus total bridge rehabilitation actions such as recoating or deck replacement, versus functional improvements and bridge replacement. Higher failure costs directly increase the benefits of repair actions, but only indirectly affect the benefits of total bridge rehabilitation, and have little or no effect on functional improvements or replacement. The NAT was instrumental in discovering the importance of this effect.

The sensitivity of the Pontis models to failure cost has caused some discomfort because failure costs are relatively difficult to understand and use. In Pontis 5.2, failure costs are to be eliminated entirely, in favor of including health index in the utility function.

2.2.7 Functional improvement models

Functional improvement models in PLAT and MOOS are similar, but not identical. Both systems use level of service standards to identify functional deficiencies. MOOS obtains these standards from the Pontis database, where they can vary by functional class, traffic volume class, on/off the National Highway System, and on/off the State highway system. The PLAT standards vary only by functional class (Figure 2.17).



Standards	Level of service					Design			
Functional class	Lane width (m)	Shoulder width (m)	Vertical clearance (m)	Operating rating (tons)	Default speed (kph)	Lane width (m)	Shoulder width (m)	Vertical clearance (m)	Replacement swell factor
01 Rural Interstate	3.4	0.9	4.3	41	94	3.7	4.9	4.9	1.2
02 Rural Other Princ	3.4	0.9	4.3	36	87.8	3.7	2.4	4.4	1.2
06 Rural Minor Arterial	3.4	0.9	4.3	36	80	3.7	2.4	4.4	1.2
07 Rural Mjr Collector	3.4	0.9	4.3	33	80	3.7	2.4	4.4	1.2
08 Rural min Collector	3.4	0.9	4.3	30	40	3.7	2.4	4.4	1.2
09 Rural Local	3.4	0.9	4.3	27	40	3.7	2.4	4.4	1.2
11 Urban Interstate	3.4	0.9	4.3	41	91	3.7	4.9	4.9	1.2
12 Urban Fwy/Expwy	3.4	0.9	4.3	36	83	3.7	2.4	4.9	1.2
14 Urban Other Princ	3.4	0.9	4.3	36	83	3.7	2.4	4.4	1.2
16 Urban Minor Arterial	3.4	0.9	4.3	36	48	3.7	2.4	4.4	1.2
17 Urban Collector	3.4	0.9	4.3	33	48	3.7	2.4	4.4	1.2
19 Urban Local	3.4	0.9	4.3	27	32	3.7	2.4	4.4	1.2

Short bridge rule: If length<= 60 m. then des/req width must be >= 0.9 times aroadwidth

Bypass speed factor 0.9

Figure 2.17. PLAT level of service and design standards

User cost models in MOOS and PLAT both use accident risk models (Thompson et al. 1999) and truck height/weight histograms (Sobanjo and Thompson 2004) from Florida DOT research. These are both still recognized as the only authoritative source of this information. PLAT contains a user cost model for movable bridge openings (Sobanjo and Thompson 2004), while MOOS does not.

The two models produced similar project lists, costs, and benefits for functional improvement projects.

2.2.8 Scoping models

A major innovation in the PLAT, compared to Pontis, is a more realistic set of models for deciding on the scope of work in each project. Both systems rely on a new classification of actions not supplied with Pontis. PLAT has a scheme consisting of 49 preservation action subcategories (Figure 2.18), plus do-nothing, widening, raising, strengthening, and replacement, for a total of 54 categories. MOOS has 32 categories, which are:

0	Do nothing
11	Replace structure
21	Widen
22	Raise
23	Strengthen
24	Scour Mitigation

25	Seismic Retrofit
26	Fatigue Mitigate
27	Other Mitigation
31	Total system replacement (TSR) - Superstructure
32	TSR Deck Structure
33	TSR Wearing Surface
34	TSR Steel Coating
35	TSR Expansion Joints
36	TSR Railings
37	TSR Bearings
41	Maintenance, repair, and rehabilitation (MRR) - Deck Elements
42	MRR Steel Elements
43	MRR Steel Coating
44	MRR Concrete Elem
45	MRR Timber Elements
46	MRR Expansion Joints
47	MRR Bearings
48	MRR Railings
49	MRR Other Elements
51	Routine Maintenance
52	Temporary Cribbing
53	Remove Structure
61	Design & Engineering
62	Mobilization
63	Maintenance of Traffic
71	Custom Scope Item

Unlike PLAT, the MOOS system includes actions for risk mitigation, and also has categories for indirect costs. For preservation actions, MOOS distinguishes total system replacement (TSR) actions — which affect the entirety of an element — from MRR actions that affect only portions of an element. PLAT provides special handling of paint system replacement and deck replacement, which approximate the functionality of the TSR actions in MOOS.

To develop a project scope, both systems begin with the most recent Pontis inspection results, and deteriorate each element to the start of the year when action is being considered. Both systems then use the Pontis network optimization model to specify actions that are considered “justified” by the deteriorated conditions.

At this point, the two systems diverge. PLAT groups similar action types together across elements, and applies scale feasibility thresholds. Maximum and minimum levels are set for each action sub-category, as a weighted percent of total element quantity. If a scope item satisfies the thresholds, then it is included in the project.

The PLAT then expands each element action to include condition states where the action isn’t optimal on its own, but where it would be applicable. For example, if painting condition state 4, it would also throw in condition states 2 and 3, since the marginal cost is reduced when mobilization and MOT are already sunk costs. The combination of scale feasibility and quantity expansion, leads to projects that are of realistic size for implementation.

White cells represent valid sub-categories; numbers refer to footnotes

		Object	Action Category 100-Replace	200-Rehab	300-Repair	400-Maint
Materials	0	Other material	▨	▨	▨	1
	1	Deck		2	3	4
	2	Steel/coat (incl metal)	5		6	7
	3	Concrete	▨		8	9
	4	Timber	▨		▨	
	5	Masonry	▨		▨	
	6	MSE	▨		▨	
Hi-Maint	10	Other element	▨	▨	▨	▨
	11	Joint				
	12	Joint seal		▨	▨	▨
	13	Bearing (incl p/h)			▨	
	14	Railing		▨	▨	▨
Drainage	21	Slope prot			▨	▨
	22	Channel	▨		▨	
	23	Drain sys			▨	
Machinery	31	Machinery	10	10	10,11	10
	32	Cath prot		▨	▨	▨
Major	41	Beam		▨	▨	▨
	42	Truss/arch/box		▨	▨	▨
	43	Cable			▨	▨
	44	Substr elem (exc cap)	12	▨	▨	▨
	45	Culvert		▨	▨	▨
	46	Appr slab		13	▨	
Appurtenances	51	Pole/sign		▨	▨	▨

Footnotes

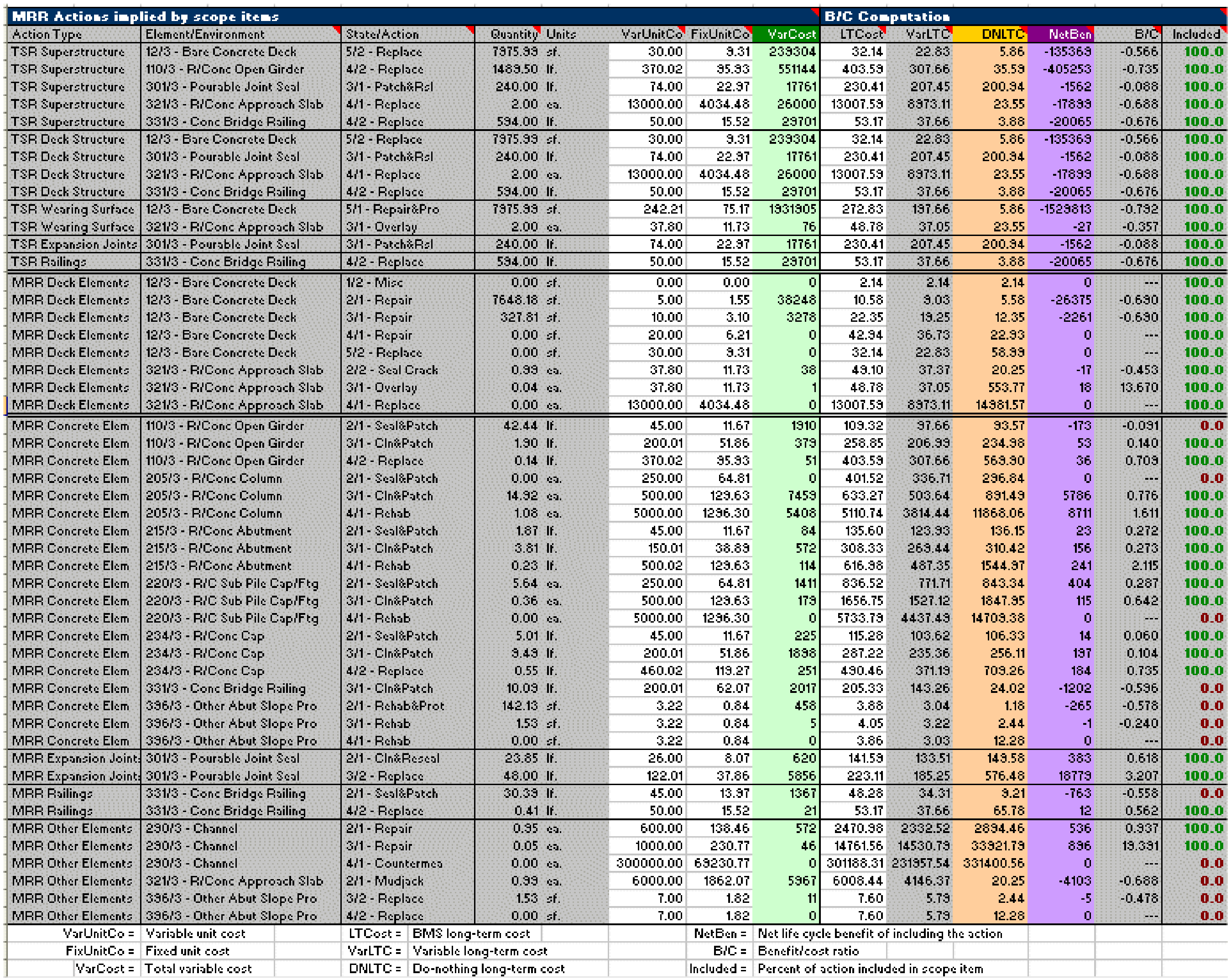
1. Wash structure
2. Rehab deck and replace overlay
3. Repair deck and substrate
4. Repair potholes
5. Replace paint system
6. Spot paint
7. Restore top coat
8. Clean rebar and patch
9. Patch minor spalls
10. Includes electrical, hydraulic, and mechanical elements
11. Repair and lubricate
12. Includes fenders, dolphins, and pile jackets
13. Mudjacking

Figure 2.18. PLAT action categories and sub-categories

MOOS began with the experience of PLAT, and extended the concept further. It first expands each feasible action by making a list, for all elements and condition states, of all possible actions belonging to the same action type (Figure 2.19). For each of these, it calculates fixed and variable costs, the life cycle cost of the action and of doing nothing, and the benefit. It computes a new benefit based on variable costs, to determine whether each additional action becomes attractive when fixed costs are already sunk. Individual actions having a positive net benefit, are combined across the action type, to make a scope item.

After collapsing the MR&R actions into scope items, a more compact list is created, as in Figure 2.20. Functional improvement and mitigation actions are added to the list. The cost of each scope item is divided by the maximum possible cost of that scope item, as a measure of scale. This result is then compared with a minimum threshold for the action type, to determine whether the scope item is sufficiently large. If a scope item has a positive net benefit and satisfies its scale threshold, then it can be included in the project.

One complication that arises in MOOS, but not in PLAT, is that the same element may be addressed by more than one scope item. When this happens, MOOS follows an order of precedence. For example, if a project includes both deck replacement and deck repairs, replacement takes precedence.



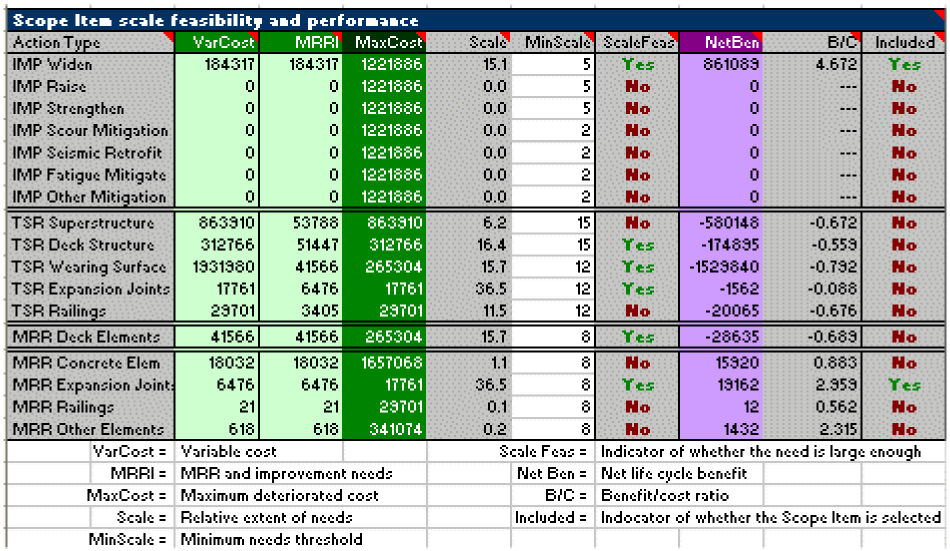
MRR Actions implied by scope items								B/C Computation					
Action Type	Element/Environment	State/Action	Quantity	Units	VarUnitCo	FixUnitCo	VarCost	LTCost	VarLTC	DNLTC	NetBen	B/C	Included
TSR Superstructure	12/3 - Bare Concrete Deck	5/2 - Replace	7975.99	sf.	30.00	9.31	239304	32.14	22.83	5.86	-135369	-0.566	100.0
TSR Superstructure	110/3 - R/Conc Open Girder	4/2 - Replace	1489.50	lf.	370.02	95.93	551144	403.59	307.66	35.59	-405253	-0.735	100.0
TSR Superstructure	301/3 - Pourable Joint Seal	3/1 - Patch&Rsl	240.00	lf.	74.00	22.97	17761	230.41	207.45	200.94	-1562	-0.088	100.0
TSR Superstructure	321/3 - R/Conc Approach Slab	4/1 - Replace	2.00	ea.	13000.00	4034.48	26000	13007.59	8973.11	23.55	-17899	-0.688	100.0
TSR Superstructure	331/3 - Conc Bridge Railing	4/2 - Replace	594.00	lf.	50.00	15.52	29701	53.17	37.66	3.88	-20065	-0.676	100.0
TSR Deck Structure	12/3 - Bare Concrete Deck	5/2 - Replace	7975.99	sf.	30.00	9.31	239304	32.14	22.83	5.86	-135369	-0.566	100.0
TSR Deck Structure	301/3 - Pourable Joint Seal	3/1 - Patch&Rsl	240.00	lf.	74.00	22.97	17761	230.41	207.45	200.94	-1562	-0.088	100.0
TSR Deck Structure	321/3 - R/Conc Approach Slab	4/1 - Replace	2.00	ea.	13000.00	4034.48	26000	13007.59	8973.11	23.55	-17899	-0.688	100.0
TSR Deck Structure	331/3 - Conc Bridge Railing	4/2 - Replace	594.00	lf.	50.00	15.52	29701	53.17	37.66	3.88	-20065	-0.676	100.0
TSR Wearing Surface	12/3 - Bare Concrete Deck	5/1 - Repair&Pro	7975.99	sf.	242.21	75.17	1931905	272.83	197.66	5.86	-1529813	-0.792	100.0
TSR Wearing Surface	321/3 - R/Conc Approach Slab	3/1 - Overlay	2.00	ea.	37.80	11.73	76	48.78	37.05	23.55	-27	-0.357	100.0
TSR Expansion Joints	301/3 - Pourable Joint Seal	3/1 - Patch&Rsl	240.00	lf.	74.00	22.97	17761	230.41	207.45	200.94	-1562	-0.088	100.0
TSR Railings	331/3 - Conc Bridge Railing	4/2 - Replace	594.00	lf.	50.00	15.52	29701	53.17	37.66	3.88	-20065	-0.676	100.0
MRR Deck Elements	12/3 - Bare Concrete Deck	1/2 - Misc	0.00	sf.	0.00	0.00	0	2.14	2.14	2.14	0	---	100.0
MRR Deck Elements	12/3 - Bare Concrete Deck	2/1 - Repair	7648.18	sf.	5.00	1.55	38248	10.58	9.03	5.58	-26375	-0.690	100.0
MRR Deck Elements	12/3 - Bare Concrete Deck	3/1 - Repair	327.81	sf.	10.00	3.10	3278	22.35	19.25	12.35	-2261	-0.690	100.0
MRR Deck Elements	12/3 - Bare Concrete Deck	4/1 - Repair	0.00	sf.	20.00	6.21	0	42.94	36.73	22.93	0	---	100.0
MRR Deck Elements	12/3 - Bare Concrete Deck	5/2 - Replace	0.00	sf.	30.00	9.31	0	32.14	22.83	58.99	0	---	100.0
MRR Deck Elements	321/3 - R/Conc Approach Slab	2/2 - Seal Crack	0.99	ea.	37.80	11.73	38	49.10	37.37	20.25	-17	-0.453	100.0
MRR Deck Elements	321/3 - R/Conc Approach Slab	3/1 - Overlay	0.04	ea.	37.80	11.73	1	48.78	37.05	553.77	18	13.670	100.0
MRR Deck Elements	321/3 - R/Conc Approach Slab	4/1 - Replace	0.00	ea.	13000.00	4034.48	0	13007.59	8973.11	14981.57	0	---	100.0
MRR Concrete Elem	110/3 - R/Conc Open Girder	2/1 - Seal&Patch	42.44	lf.	45.00	11.67	1910	109.32	97.66	93.57	-173	-0.091	0.0
MRR Concrete Elem	110/3 - R/Conc Open Girder	3/1 - Cln&Patch	1.90	lf.	200.01	51.86	379	258.85	206.99	234.98	53	0.140	100.0
MRR Concrete Elem	110/3 - R/Conc Open Girder	4/2 - Replace	0.14	lf.	370.02	95.93	51	403.59	307.66	569.90	36	0.709	100.0
MRR Concrete Elem	205/3 - R/Conc Column	2/1 - Seal&Patch	0.00	ea.	250.00	64.81	0	401.52	336.71	296.84	0	---	0.0
MRR Concrete Elem	205/3 - R/Conc Column	3/1 - Cln&Patch	14.92	ea.	500.00	129.63	7459	633.27	503.64	891.49	5786	0.776	100.0
MRR Concrete Elem	205/3 - R/Conc Column	4/1 - Rehab	1.08	ea.	5000.00	1296.30	5408	5110.74	3814.44	11868.06	8711	1.611	100.0
MRR Concrete Elem	215/3 - R/Conc Abutment	2/1 - Seal&Patch	1.87	lf.	45.00	11.67	84	135.60	123.93	136.15	23	0.272	100.0
MRR Concrete Elem	215/3 - R/Conc Abutment	3/1 - Cln&Patch	3.81	lf.	150.01	38.89	572	308.33	269.44	310.42	156	0.273	100.0
MRR Concrete Elem	215/3 - R/Conc Abutment	4/1 - Rehab	0.23	lf.	500.02	129.63	114	616.98	487.35	1544.97	241	2.115	100.0
MRR Concrete Elem	220/3 - R/C Sub Pile Cap/Ftg	2/1 - Seal&Patch	5.64	ea.	250.00	64.81	1411	836.52	771.71	843.34	404	0.287	100.0
MRR Concrete Elem	220/3 - R/C Sub Pile Cap/Ftg	3/1 - Cln&Patch	0.36	ea.	500.00	129.63	179	1656.75	1527.12	1847.95	115	0.642	100.0
MRR Concrete Elem	220/3 - R/C Sub Pile Cap/Ftg	4/1 - Rehab	0.00	ea.	5000.00	1296.30	0	5733.79	4437.49	14709.38	0	---	0.0
MRR Concrete Elem	234/3 - R/Conc Cap	2/1 - Seal&Patch	5.01	lf.	45.00	11.67	225	115.28	103.62	106.33	14	0.060	100.0
MRR Concrete Elem	234/3 - R/Conc Cap	3/1 - Cln&Patch	9.49	lf.	200.01	51.86	1898	287.22	235.36	256.11	197	0.104	100.0
MRR Concrete Elem	234/3 - R/Conc Cap	4/2 - Replace	0.55	lf.	460.02	119.27	251	490.46	371.19	709.26	184	0.735	100.0
MRR Concrete Elem	331/3 - Conc Bridge Railing	3/1 - Cln&Patch	10.09	lf.	200.01	62.07	2017	205.33	143.26	24.02	-1202	-0.596	0.0
MRR Concrete Elem	396/3 - Other Abut Slope Pro	2/1 - Rehab&Prot	142.13	sf.	3.22	0.84	458	3.88	3.04	1.18	-265	-0.578	0.0
MRR Concrete Elem	396/3 - Other Abut Slope Pro	3/1 - Rehab	1.53	sf.	3.22	0.84	5	4.05	3.22	2.44	-1	-0.240	0.0
MRR Concrete Elem	396/3 - Other Abut Slope Pro	4/1 - Rehab	0.00	sf.	3.22	0.84	0	3.86	3.03	12.28	0	---	0.0
MRR Expansion Joints	301/3 - Pourable Joint Seal	2/1 - Cln&Reseal	23.85	lf.	26.00	8.07	620	141.59	133.51	149.58	383	0.618	100.0
MRR Expansion Joints	301/3 - Pourable Joint Seal	3/2 - Replace	48.00	lf.	122.01	37.86	5856	223.11	185.25	576.48	18779	3.207	100.0
MRR Railings	331/3 - Conc Bridge Railing	2/1 - Seal&Patch	30.39	lf.	45.00	13.97	1367	48.28	34.31	9.21	-763	-0.558	0.0
MRR Railings	331/3 - Conc Bridge Railing	4/2 - Replace	0.41	lf.	50.00	15.52	21	53.17	37.66	65.78	12	0.562	100.0
MRR Other Elements	290/3 - Channel	2/1 - Repair	0.95	ea.	600.00	138.46	572	2470.98	2332.52	2894.46	536	0.937	100.0
MRR Other Elements	290/3 - Channel	3/1 - Repair	0.05	ea.	1000.00	230.77	46	14761.56	14530.79	33921.79	896	19.391	100.0
MRR Other Elements	290/3 - Channel	4/1 - Countermea	0.00	ea.	300000.00	69230.77	0	301188.31	231957.54	331400.56	0	---	0.0
MRR Other Elements	321/3 - R/Conc Approach Slab	2/1 - Mudjack	0.99	ea.	6000.00	1862.07	5967	6008.44	4146.37	20.25	-4103	-0.688	0.0
MRR Other Elements	396/3 - Other Abut Slope Pro	3/2 - Replace	1.53	sf.	7.00	1.82	11	7.60	5.79	2.44	-5	-0.478	0.0
MRR Other Elements	396/3 - Other Abut Slope Pro	4/2 - Replace	0.00	sf.	7.00	1.82	0	7.60	5.79	12.28	0	---	0.0

VarUnitCo = Variable unit cost
FixUnitCo = Fixed unit cost
VarCost = Total variable cost
LTCost = BMS long-term cost
VarLTC = Variable long-term cost
DNLTC = Do-nothing long-term cost
NetBen = Net life cycle benefit of including the action
B/C = Benefit/cost ratio
Included = Percent of action included in scope item

Figure 2.19. Listing of detailed MR&R actions in MOOS

Both the PLAT and MOOS use scope expansion and scale thresholds. A subtle but important difference is that they apply these in opposite order: PLAT evaluates scale feasibility before expanding the scope, while MOOS does these in the opposite order. This would be expected to yield fewer projects in the PLAT, since it is harder to pass the scale threshold, and the resulting projects would be larger on average.

This turned out to be the case. Under the scenarios that were most similar between the two systems, MOOS programmed 502 projects in the first year, with an average cost of $589k per bridge. PLAT programmed 1013 projects with an average cost of $292k.



Scope Item scale feasibility and performance

Action Type	VarCost	MRRI	MaxCost	Scale	MinScale	ScaleFeas	NetBen	B/C	Included
IMP Widen	184317	184317	1221886	15.1	5	Yes	861089	4.672	Yes
IMP Raise	0	0	1221886	0.0	5	No	0	---	No
IMP Strengthen	0	0	1221886	0.0	5	No	0	---	No
IMP Scour Mitigation	0	0	1221886	0.0	2	No	0	---	No
IMP Seismic Retrofit	0	0	1221886	0.0	2	No	0	---	No
IMP Fatigue Mitigate	0	0	1221886	0.0	2	No	0	---	No
IMP Other Mitigation	0	0	1221886	0.0	2	No	0	---	No
TSR Superstructure	863910	53788	863910	6.2	15	No	-580148	-0.672	No
TSR Deck Structure	312766	51447	312766	16.4	15	Yes	-174895	-0.559	No
TSR Wearing Surface	1931980	41566	265304	15.7	12	Yes	-1529840	-0.792	No
TSR Expansion Joints	17761	6476	17761	36.5	12	Yes	-1562	-0.088	No
TSR Railings	29701	3405	29701	11.5	12	No	-20065	-0.676	No
MRR Deck Elements	41566	41566	265304	15.7	8	Yes	-28635	-0.689	No
MRR Concrete Elem	18032	18032	1657068	1.1	8	No	15920	0.883	No
MRR Expansion Joint	6476	6476	17761	36.5	8	Yes	19162	2.959	Yes
MRR Railings	21	21	29701	0.1	8	No	12	0.562	No
MRR Other Elements	618	618	341074	0.2	8	No	1432	2.315	No

VarCost = Variable cost
MRRI = MRR and improvement needs
MaxCost = Maximum deteriorated cost
Scale = Relative extent of needs
MinScale = Minimum needs threshold
Scale Feas = Indicator of whether the need is large enough
Net Ben = Net life cycle benefit
B/C = Benefit/cost ratio
Included = Indicator of whether the Scope Item is selected

Figure 2.20. Listing of scope items in MOOS

2.2.9 Data processing and preparation

In order to compare the results of the two systems, a Pontis database suitable for both systems was prepared. This began with the full August 2008 Pontis database obtained from FDOT. From this database, a smaller file was produced by deleting all structures whose owner codes were not 1, 31, or 33, thus eliminating bridges not owned by the state. District 6 bridges with owner code 31 were also deleted, as directed by FDOT. Structures whose service type codes were outside the 0-9 NBI range, were found to be non-bridge structures and were also deleted. This left a database of 6529 state highway bridges.

It was found that some of the model inputs in the FDOT Pontis database differed from the models delivered in earlier studies (Thompson et al, 1999, Sobanjo and Thompson, 2001). Most importantly, the deterioration model was absent and certain user cost factors had changed. Two elements were added. To ensure a consistent analysis, the models were restored to a level consistent with earlier research and current inspections. The following changes were made:

- Deleted elements that had definitions in the FDOT database but no instances in the eleminsp table:
  14, 18, 22, 26, 27, 40, 44, 48, 52, 53, 176, 225, 226, 227, 228, 229 (all "non-FDOT element"), 115 (P/S Conc Stringer), 130 (unpainted steel deck truss), 145 (other arch), 480-486 (mast arms).
- Removed from the mrractdf table one instance of akey=3 (element 30) which appeared to be erroneous data.
- Deleted all records in the condumdl and actmodls tables having mokey='01', since those are not used by Pontis, PLAT, or MOOS.
- Imported from an archived copy of PLAT, all the deterioration and cost models used in the 2001-2004 study. No effort was made to update these models for subsequent inspections or inflation. Such adjustments are planned for later in the present study.
- Added models for new elements that were not present in the PLAT, but which have small numbers of inspections in the database: 154 – Prestressed concrete

floor beams (7 bridges); and 160 – Unpainted steel pins and hangers (5 bridges).

- Deleted the record for element 394/ state 2/ action 2 in mrractdf and actmodls since this action did not have a name and it could not be determined what models would apply.
- For elements 154 and 160, and for 7 new MR&R actions that were found, missing data were provided by copying from similar elements, states, and actions.

In addition, both systems require a new action classification scheme, where each Pontis MRR action is associated with higher-level categories. For PLAT, most of the action codes had already been developed, so only the new elements and actions needed to be added. These are stored in the PLAT Excel file.

For MOOS, the process started with action types for CoRe elements, states, and actions, which were developed in the NCHRP 12-67 study. Action type codes for non-CoRe elements were added manually based on engineering judgment. These are stored in the MOOS intermediate database.

Finally, it was necessary to reconcile, to the extent possible, the diverse analytical input parameters used in the two systems. PLAT/NAT parameters were left entirely unchanged, except to change the first program year to 2009, and disable the NBI translator (which is being revised in a parallel task). For MOOS, a variety of changes were necessary:

- Disabled the NBI translator
- Set the bridge level analysis to optimize the first intervention and to use condition thresholds for consequent interventions. This is the combination that is most similar to the PLAT analysis.
- Enabled the failure risk model. Ultimately, the best scenarios were developed when the failure risk model was turned off, and health index was given 75% of the utility function weight.
- Activated deterioration between the last inspection and the base year of the analysis.
- Set the display units to US Customary.
- Set the fixed cost of mobilization to $2000 and the fixed cost per lane for MOT to $2000. Alternative values of these parameters were also investigated, and found to have a significant effect on the programming of very small maintenance actions.
- Set the variable cost of mobilization to 11% of direct cost. This level, in combination with the $2000 fixed cost, yielded total mobilization costs close to the PLAT numbers.
- Set the variable cost of MOT to 15% of direct cost. This level, combined with the $2000 fixed cost per lane, yielded total MOT costs close to the PLAT numbers.
- Set the variable cost of engineering to 10% of direct cost, to be consistent with the PLAT.
- Set the discount rate to 0.9525 to agree with PLAT.

- Set the first year of the program to 2009, 9 years in the program horizon, and a 9 year rest period. Shorter rest periods, allowing multiple interventions on a bridge, were also investigated.
- In the Pontis database, changed unit accident costs and user cost weight to agree with the PLAT.
- Verified that other analysis inputs in the Pontis database were consistent with PLAT.

2.2.10 Comparison of results

Other than items specifically provided on the model worksheets, both PLAT and MOOS load most of their model inputs from the Pontis database. Thus they are assured of using the same values. Neither system writes any information back to the Pontis database.

Most of the data processing work under this task was exploratory data analysis, modifying the inputs to see the effect on system outputs. Some of the detailed results are reported in the sections above. The search was directed by two organizing objectives:

1. To try to get PLAT/NAT and MOOS to produce similar project lists that fully utilize a budget of $295 million for each of the nine years for the 6529 state highway bridges.
2. To try to maximize the health index of the inventory at the end of the nine year period.

It was found that PLAT/NAT was most effective in fully utilizing the available funding. However, it tended to produce more element replacement projects than would be realistic. Some of the projects had unrealistically low cost estimates, which could be remedied by a simple indirect cost model such as the one used in MOOS. Figure 2.21 shows the annual expenditure graph in the NAT, compared to the same graph in MOOS for a matched set of scenarios. Both show that expenditures are very close to the budget.

In MOOS, it was possible to fully utilize the budget only when the failure cost model was disabled, health index was given 75% or more of utility function weight, and the rest period was set to 5 years or less. This scenario also produced higher ending condition levels than other MOOS scenarios.

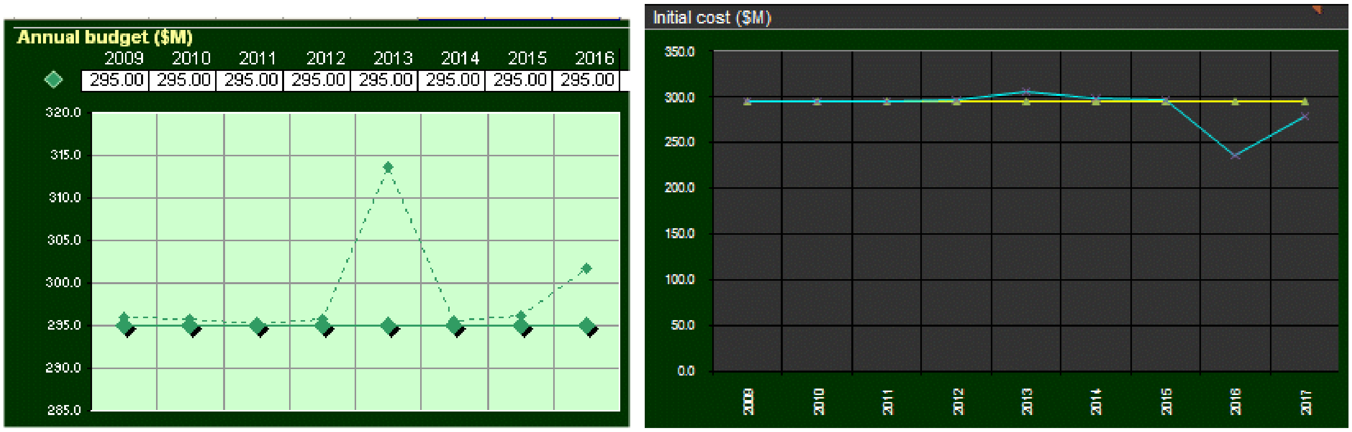
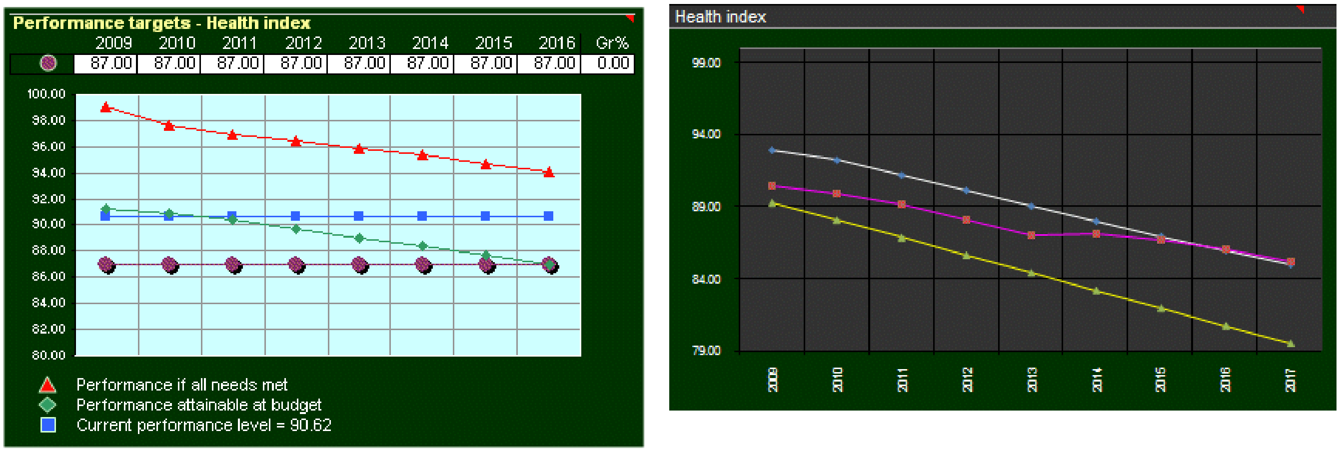


Figure 2.21. Comparison of expenditures vs. budget, NAT (left) and MOOS

Neither system was able to maintain the present health index of 90.62 under the default deterioration model. However, MOOS gives more control over this result because of the utility function. Giving more weight to health index, relative to life cycle cost, invariably led to better ending conditions. A simple utility function capability, that combines only life cycle cost and health index, could be added to the PLAT/NAT system and would significantly improve policy sensitivity. Figure 2.22 compares the performance results for the two models. In both cases the resulting health index was between 86 and 87.

Task 1 found PLAT/NAT to be quite sensitive to deterioration and unit costs. MOOS was subjected to a more limited sensitivity analysis with Florida data and found to be equally sensitive to these inputs. It was easier in both systems to maintain a high health index when the transition time from state 1 to state 2 was increased. This is a very likely outcome of the deterioration investigation planned for later in the present study.

With the deterioration models currently in the NAT, the highest attainable health index under the best scenario tested, was 86.92. If the transition time from state 1 to state 2 is systematically doubled, this health index increases to 90.27. If doubled again, the final health index is 92.06. This is a significant difference. It indicates the importance of gaining a more confident quantitative understanding of deterioration of bridges in relatively good condition, as is planned in the present study.



	2009	2010	2011	2012	2013	2014	2015	2016	Gr%
●	87.00	87.00	87.00	87.00	87.00	87.00	87.00	87.00	0.00

Figure 2.22. Comparison of health index, NAT (left) and MOOS

3. Improved NBI Translator

This section summarizes the findings of a study on improvement of the FHWA's NBI Translator, addressing the generation of NBI ratings from the Pontis element inspection data on Florida bridges. Using the element inspection data from Pontis for years 2007 and 2008 on Florida bridges, the NBI Translator model developed from a previous study in Florida, was extensively reviewed with the goal of modifying some of the algorithms in order to reduce the errors of translated ratings.

3.1 Introduction

Due to Federal Highway Administration (FHWA) requirements, many transportation agencies have to report their bridge network condition using the National Bridge Inventory (NBI) ratings. But many of these agencies are collecting their bridge condition data at the element level. An existing program, the FHWA's Bridge Management System National Bridge Inventory (NBI) translator, or the BMSNBI program, is currently used to generate required condition ratings as performance measures for bridge funding programs. Despite its many useful features, some problems have been identified with using the BMSNBI and some solutions have been suggested as improvements to translation of element condition data to NBI ratings (Al-Wazeer et al. 2007, Sobanjo et al. 2008). Florida conducts its bridge inspection based on AASHTO's Commonly Recognized (CoRe) Elements, for the Pontis® BMS software but also needs to translate its inspection results into NBI condition ratings. It is one of the objectives of Florida to improve its NBI rating translation process. To aid this objective, Florida has available, in addition to the element-level condition data, Florida bridge inspection data where the NBI inspections were carried out simultaneously with the bridge element-based inspections. Florida assigns NBI ratings for all its element-level inspections and uses the FHWA's NBI Translator as a guide. These NBI inspected ratings would serve as the basis for evaluating the results of translations by the methodology proposed in this study.

In the literature review, only two documented efforts were identified, related to the translation of element inspection records into NBI ratings -- the report on the original development of the NBI Translator (Hearn et al. 1997), and a report by Al-Wazeer et al. (2007), using the neural network technique. Aldemir-Bektas and Smadi (2008) also presented a discussion on the accuracy of the original NBI translator but did not develop any new translator model. Sobanjo et al. (2008) developed a preliminary model for the NBI translation process for Florida bridges, presenting a more detailed review of the original BMSNBI model and the effort by Wazeer et al. (2007).

The objective of the study being reported here is an effort to improve on the model of Sobanjo et al. (2008). First, the underlying methodology of the Translator Program is discussed, including the concepts of estimating element condition index, translating the index to an element NBI condition rating. Aggregation of the element condition index for each bridge component (deck, superstructure, substructure, culvert) is then discussed, including the attempts to determine element weighting factors (similar to criteria weights), using multiple regression and optimization techniques. The data flow scheme and database structure is discussed next, along with a description of the computer program developed to implement the proposed methodology. Modification of the methodology in order to improve accuracy of translation of the ratings is also presented, where regression factors are utilized to improve the results. Case studies on translated ratings at specific bridges are done to ascertain the reasons for error in some translations. The results are presented using tables and figures to show the accuracy at the various bridge components in terms of mean translated ratings and absolute differences at each known inspected

NBI rating. Finally, assuming the Markov Chain model, the effect of the translated ratings on the deterioration models is demonstrated at a specific bridge over a 70-year service life.

3.2. Methodology

The proposed methodology tries to incorporate the fundamentals and process of bridge inspection at both at the element level and the NBI standards. First there are typically, multiple Commonly Recognized or CoRe elements at each bridge component; these have to be grouped together, i.e., each element has to be assigned a specific bridge component, except for the case of deck slabs, which are designated as both decks and superstructures. The second issue is that under element-based inspection, each element is evaluated and given a condition description (percentage of quantity in each state), which can be converted to a single point condition index. The index will vary from 0 to 1, representing the worst and excellent conditions respectively. Under the NBI inspection, single ratings are assigned to the bridge component, ranging from 0 to 9, similarly representing the extreme possible conditions. The goal here then is to aggregate these indexes into the corresponding NBI rating for the bridge component. In evaluating the bridge component for the NBI ratings, the bridge inspector would consider and have a perception of the relative importance of each constituent element, in order to arrive at a single overall value of the rating. It is therefore very important to estimate and incorporate a reliable set of relative criteria weights for each element in order to calculate an aggregate component rating.

3.2.1 Condition index and component ratings

In element-based inspection programs such as Pontis, deteriorated condition states are listed for each element. Field inspection will involve measuring or observing the relative quantity or proportion of the element in each of the prescribed states. For a bridge element, the proposed Translator Program utilizes the proportion of the element in various deteriorated states to calculate an element condition index, ranging from 0 for the failed state, to 1 for the excellent condition state, as shown in the following equation:

$$c_i = \frac{1}{n_i}\sum_{1}^{n_i}\left(\frac{pct_{ij}}{100}\right)(n_i - j + 1) \tag{3.1}$$

where,

c_i = the computed condition index of element *i*, $0 \leq c_i \leq 1$.

n_i = total listed number (in Pontis *statecnt* field) of condition states *j* for bridge element *i*, with $j = 1,2,..\ n_i$.

pct_{ij} = percentage of bridge quantity in state *j* for element *i*.

It should be noted that this equation 3.1 accommodates a failed state, beyond the listed condition states in Pontis (*statecnt* field data). While Pontis also considers the failure state as an additional state, the condition state count indicated in the *statecnt* field does not include the failed state. For instance, element no. 12 has five defined condition states (*statecnt* = 5): state 1 – no damage; state 2 – distress <= 2%; state 3 –2 to 10% distress; state 4 – 10 to 25% distress; and state 5 – distress over 25%. In this report, Pontis *statecnt* values will still be used to reference the number of states. In other words, elements can have 3, 4, or 5 states, going strictly by the *statecnt* numbers.

The next issue is to relate the condition index values to the corresponding deterioration states as illustrated in Figure 3.1. Based on a linear assumption of relationship between deterioration states and the condition index, the expected state of the element, i.e., state 1, state 2,..down to state $n_i +1$ (failed state), can be estimated as follows:

$$c_i = (n_i + 1 - s_i) / s_i \tag{3.2}$$

or

$$s_i = 1 + n_i (1 - c_i) \tag{3.3}$$

where,

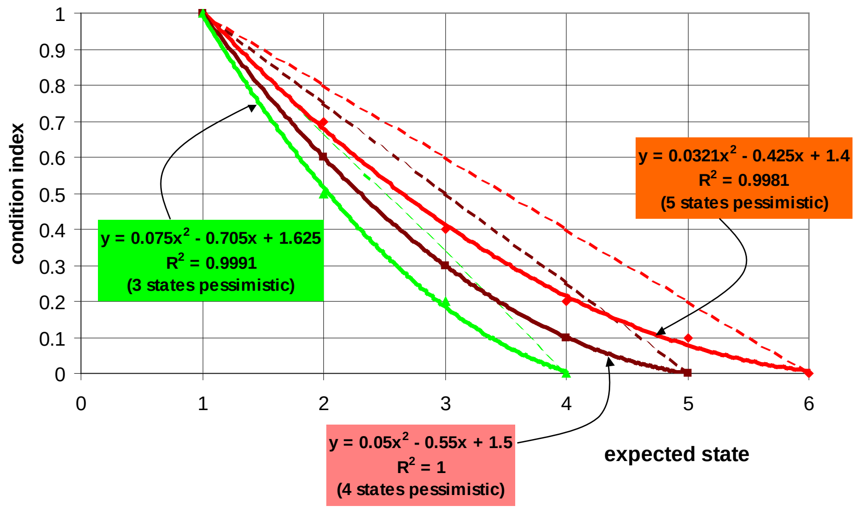
s_i = the expected condition state of element *i*, with $j = 1,2,..\ n_i+1$.
c_i = the computed condition index of element *i*, $0 \le c_i \le 1$.
n_i = total listed number (in Pontis) of condition states *j* for bridge element *i*, with $j = 1,2,..\ n_i$.

Equations 3.1 and 3.3 can be combined and expressed as:

$$s_i = n_i + 1 - \sum_{1}^{n_i} \left(\frac{pct_{ij}}{100} \right) (n_i + 1 - j) \tag{3.4}$$

where,

s_i = the expected condition state of element *i*, with $j = 1,2,..\ n_i+1$.
n_i = total listed number (in Pontis) of condition states *j* for bridge element *i*, with $j = 1,2,..\ n_i$.
pct_{ij} = percentage of bridge quantity in state *j* for element *i*.



state	3-state index linear	3-state index pessimistic	4-state index linear	4-state index pessimistic	5-state index linear	5-state index pessimistic
1	1.00	1.00	1.00	1.00	1.00	1.00
2	0.67	0.50	0.75	0.60	0.80	0.70
3	0.33	0.20	0.50	0.30	0.60	0.40
4	0.00	0.00	0.25	0.10	0.40	0.20
5			0.00	0.00	0.20	0.10
6					0.00	0.00

Figure 3.1. Suggested model for variation of bridge element condition index with state

Equations 3.2 to 3.4 imply that element condition index increases linearly with the expected condition state. As shown in Figure 3.1, for all cases, the condition index will have a value 1 when all elements' quantity are in state 1, the best condition state. When the element is wholly in the failed state, then the condition index is 0. For a 5-state element, i.e., quantities are measured for five condition states, the index for the linear model (equations 3.1 and 3.2) will be 0.4 when the element is wholly in state 4. Likewise, in a 3-state element, the index will be 0.667 when the element is wholly in state 2 and 0.333 when in state 3.

But bridge inspection practice will not necessarily support the linear model described above. The methodology of the proposed Translator Program is suggesting a more pessimistic nonlinear approach, described in the following statements, including some assumptions. As the element condition worsens, the inspectors would rate the index lower than the values listed in the linear model. For example, in the 5-state element, if the element is wholly in state 2, the condition index will be lower than the 0.8 suggested in Figure 3.1; the condition index in this state is assumed to be a bit lower, say 0.7. The remaining indexes are as shown in Figure 3.1, based on the same reasoning. In a 3-state element, if 100% of the element is in state 2, the condition index is suggested to be 0.5 rather than the 0.667 of the linear model, and when the element is wholly in state 3, the index will be 0.2. For a 4-state element, when the element is wholly in state 3, it is suggested that, for the proposed nonlinear model, that the index be 0.3 instead of the 0.5 from the linear model.

The assumption of pessimistic nonlinear relation between the condition index and expected state, shown in Figure 3.1, is further developed into three regression equations 3.5, 3.6, and 3.7, that are eventually used to estimate condition index, depending the number of states listed for the element.

3-state elements: $$c_i = 0.075s_i^2 - 0.705s_i + 1.625 \tag{3.5}$$

4-state elements: $$c_i = 0.050s_i^2 - 0.550s_i + 1.500 \tag{3.6}$$

5-state elements: $$c_i = 0.032s_i^2 - 0.425s_i + 1.400 \tag{3.7}$$

where,

c_i = the computed condition index of element *i*, with $0 \le c_i \le 1$.
s_i = the expected condition state of element *i*, with $j = 1,2,.. n_i+1$.
n_i = total listed number (in Pontis) of condition states *j* for bridge element *i*, with $j = 1,2,.. n_i$.

The next step in the translation of condition index to NBI ratings is to relate the computed index to the ratings. The index varies from 0 to 1 while the NBI rating varies from 0 to 9. For practical purposes the lowest typically assigned in NBI ratings is 2 or 3 when the bridge is closed to traffic. In the previous attempts at translation of the element condition data to NBI ratings (Sobanjo et al. 2008), a linear model was assumed for this relation, and the condition index was used to prorate an NBI Rating between ratings 3 and 9. A new approach is being suggested here that, based on inspection practices, and a similar reasoning just as described above, that a pessimistic nonlinear relationship exists between the element's NBI Rating and its condition index (Figure 3.2). In addition, a minimum NBI Rating of 2 is used instead of 3, to accommodate the possibility of the element being in the failed state. An index of 0 would therefore imply a failed state, assumed as the equivalent of NBI Rating 2, while the index value 1 would correlate to excellent condition or NBI Rating 9.

As shown in Figure 3.2, a linear model would imply NBI rating 5.5 at a condition index 0.5, as well as the other values shown. But it is suggested that as the bridge element starts deteriorating from its new state (condition index 1.0) to a slightly lower value of 0.9, the inspector would rate the element NBI rating 8. With a condition index of 0.7, it is assumed that the NBI rating 6 will be assigned; at index 0.5, rating 5 will be assigned, while rating 3 will be assigned when the condition index is 0.2. The corresponding fitted regression equation is given as follows:

$$r_i = 2.674c_i^2 + 4.248c_i + 2.000 \tag{3.8}$$

where,

r_i = the computed NBI rating of element *i*, with $2 \leq r_i \leq 9$.
c_i = the computed condition index of element *i*, with $0 \leq c_i \leq 1$.

Once the condition indexes are converted to NBI ratings for each element, the “smart flags” are identified if used on each bridge and assigned to the affected bridge elements. Under element-level inspection, a smart flag is used by bridge managers to indicate a critical defect in a bridge. There are ten smart flags among Florida CoRe elements that describe the following: steel fatigue, pack rust, deck cracking, deck or slab soffit, settlement, scour, traffic impact, and section loss. The smart flag element nos. 358 and 359 are applicable to deck elements, while smart flag nos. 356, 357, 362, 363, and 370 apply to superstructure elements. Substructures are affected by smart flag nos. 360, 361, and 369. Since the smart flag data are recorded in the same format as the element condition data, an index is also computed for each smart flag. Typically one smart flag is assigned to a bridge component but occasionally two smart flags may apply to the same component. In this case, the average and the minimum (worst case) condition index of the smart flags are both applied to the NBI condition rating of the affected elements. Now each bridge element has an NBI condition rating, adjusted, if necessary by the appropriate smart flag.

The next step is to aggregate the element condition ratings into a condition rating for the parent bridge component. The equation for the computation of the component rating is as follows:

$$R = \sum_{1}^{N} r_i w_i \tag{3.9}$$

where,

R = the computed condition rating of bridge component (deck, superstructure, substructure, or culvert), with $2 \leq R \leq 9$.
r_i = the computed NBI rating of element *i*, with $2 \leq r_i \leq 9$.
w_i = weighting factor for bridge element *i*, such that at each bridge component, $\sum w_i = 1$ and $0 \leq w_i \leq 1$.
N = number of elements in the bridge component (deck, superstructure, substructure, or culvert).

	NBI Rating	
Condition Index	linear	pessimistic
0.0	2.0	2.0
0.2	3.4	3.0
0.5	5.5	5.0
0.7	6.9	6.0
0.9	8.3	8.0
1.0	9.0	9.0

Figure 3.2. Suggested model for relating Element NBI Rating to condition index

3.2.2 Estimating element relative weighting factors

As part of the methodology described above, an investigation was conducted to estimate the element weighting factors used in estimating the translated NBI ratings for the bridge components. Two approaches are proposed, including use of the regression and the optimization models. The objective here is to evaluate how much the condition of each of the constituting elements of a bridge component, contribute to the overall condition rating of the component. For example, a bridge deck component may have the element no. 12 (concrete deck) as its primary element but also have element nos. 301 (poured seal joint), and 331 (railing) as secondary elements. It is being considered that these secondary elements may also influence the overall component rating. Thus an attempt will be made to estimate such influence in terms of the relative weight factors.

In the Translation Program processes, a table *nbinewdeck* actually contains an estimate of the number of elements constituting the bridge deck component; this is done for other components (superstructure, substructure, and culverts) as well. It was observed as shown in Figure 3.3, that for the about 3,000 state-maintained bridge decks inspected in 2007, approximately 93% of the bridges have four or less elements comprising the bridge deck component. About half of the decks have three elements.

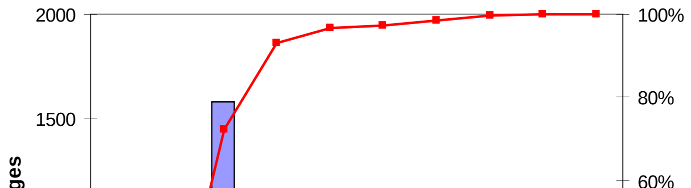


Figure 3.3. Variation in Number of Elements in State-maintained Bridge Decks

First, a multiple linear regression model, relating the inspected NBI ratings (bridge component) to the individual computed NBI ratings (from element condition index) of the constituent elements, is shown in equation 3.10.

$$R^o = w_1 r_1 + w_2 r_2 + w_3 r_3 + \ldots\ldots w_i r_i + \ldots\ldots w_N r_N \tag{3.10}$$

where,

R^o = the inspected condition rating of bridge component (deck, superstructure, substructure, or culvert), with $2 \leq R^o \leq 9$.
r_i = the computed NBI rating of element *i*, with $2 \leq r_i \leq 9$.
w_i = weighting factor for bridge element *i*, such that at each bridge component, $\sum w_i = 1$ and $0 \leq w_i \leq 1$.
N = number of elements in the bridge component (deck, superstructure, substructure, or culvert).

The goal here is to determine the regression coefficients, with a forced zero intercept or constant coefficient, and use these estimates, in a normalized form, as the relative weighting factors for the bridge elements. The element inspection data for bridge decks was rearranged such that the inspected NBI rating of the component is matched to the corresponding computed NBI ratings of the constituting elements, i.e., in the form of equation 3.10 above. A multiple regression model was then developed, with the inspected NBI ratings taken as the response variable while the element NBI ratings were regarded as the predictor variables. Table 3.1 shows the regression results.

Setting the intercept to zero, the regression coefficients estimated for each element variable were normalized to obtain a possible set of values that could be used as relative weight factors in the translation model. For instance, an example is shown in Table 3.1 for translating bridge deck ratings using the following elements: element no. 12 (BARECONCDECK); element no. 301 (POURSEALJOINT); element no. 302 (COMPRESSJOINT); and element no. 331 (CONCRAILING). The relative weighting factors, or w_i from equation 3.10, were found to be 0.84 or 84%, 0.04 or 4%, 0.07 or 7%, and 0.05 or 5% respectively (Table 3.1).

Table 3.1. Regression results for estimating relative weights for bridge deck elements

Regression Statistics	
Multiple R	0.572
R Square	0.327
Adjusted R Square	0.324
Standard Error	0.576
Observations	1012

	Coefficients	*Relative Weight Factor*	*Weight Factor*
Intercept	0		
BARECONCDECK	0.752	84%	100
POURSEALJOINT	0.035	4%	5
COMPRESSJOINT	0.064	7%	9
CONCRAILING	0.043	5%	6
sum	0.895		100%

An optimization problem was also set up to minimize (set to zero) the difference between Inspected NBI Rating and the calculated NBI rating from the element condition data. Initially, the constraints were established as follows: make the element weight factors non-zero; the sum of weights for each element must add up to one; and the objective function to be non-zero. But since the primary element, for instance element 12 in bridge decks, is always very influential in setting the NBI rating for the overall deck component, an additional constraint was added to set the rating of relative weight of this primary element at least 0.7 or 70%,

Objective function: $$delta, \delta = R^o - \sum_1^N r_i w_i = 0 \tag{3.11}$$

Constraints: $$\sum_1^N w_i = 1 \tag{3.12}$$

$$w_1 \geq 0.7 \tag{3.13}$$

$$\delta \geq 0 \tag{3.14}$$

$$w_i \geq 0 \tag{3.15}$$

where,

δ = algebraic difference between the inspected condition rating and computed (from condition index) of bridge component (deck, superstructure, substructure, or culvert), with $0 \leq \delta \leq 9$.

R^o = the inspected condition rating of bridge component (deck, superstructure, substructure, or culvert), with $2 \leq R^o \leq 9$.

r_i = the computed NBI rating of element *i*, with $2 \leq r_i \leq 9$.

w_i = weighting factor for bridge element *i*, such that at each bridge component, $\sum w_i = 1$ and $0 \leq w_i \leq 1$.

N = number of elements in the bridge component (deck, superstructure, substructure, or culvert).

Results for the runs (20 bridges each) under six different scenarios are summarized in Table 3.2 while some of the details are shown in Tables 3.3 to 3.10. To establish the scenarios, the following issues were considered: the difference between the inspected rating and the average of the elements' individual NBI ratings; and the initial weights set for the elements before running the optimization. The first issue is relevant because the search algorithms in the optimization may converge faster for a smaller difference between actual inspected NBI rating and the average of elements' NBI ratings. Based on a similar reasoning, the optimal results may be obtained faster if the initial weights are set closer to the constraint limits (primary element's weight of 0.7).

After the optimization run, done using the Solver Tool in Microsoft Excel, relative weights w_i that will satisfy the objective function and constraints stated above in equations 3.9 to 3.12, are produced as shown in Table 3.2. It could be observed that some of the results are not optimal (scenarios 2 and 7), shown in details in Tables 3.5 and 3.10 respectively. It should be noted that even the optimal results shown for the other scenarios could not be guaranteed as being global optimal results, primarily because there are several feasible solutions based on just a combination of the weights. In Tables 3.3 to 3.10, the combination small box at the lower right is the value of the objective function. While the model being considered is for four elements, with the element 12 as the primary element, these are really the four most statistically predominant elements. In the cases shown, each record has three elements each and the element not present on the bridge deck will have a rating of zero in the model.

Table 3.2. Summary of optimization runs to estimate element weight factors

Scenario	Difference between Average Translated and Inspected Rating	Initial Element Weights	Set Primary Element Constraint (0.7)?	BARECONCDECK		POURSEALJOINT		COMPRESSJOINT		CONCRAILING		REMARKS
				Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	
1	Minimal (< 0.03)	Equal*	No	0.547	0.108	0.178	0.108	0.032	0.071	0.243	0.060	optimal, local?
2	Minimal (< 0.03)	Equal*	Yes	0.702	0.077	0.083	0.077	0.012	0.037	0.061	0.078	nonoptimal.
3	Minimal (< 0.03)	Nonequal#	Yes	0.719	0.083	0.126	0.083	0.022	0.041	0.133	0.069	optimal, local?
4	About 0.4	Equal*	No	0.575	0.064	0.072	0.064	0.101	0.066	0.253	0.018	optimal, local?
5	About 0.4	Nonequal#	Yes	0.744	0.029	0.061	0.029	0.080	0.039	0.115	0.015	optimal, local?
6	Large (>2.0)	Equal*	No	0.198	0.033	0.233	0.033	0.344	0.055	0.225	0.040	optimal, local?
7	Large (>2.0)	Nonequal#	Yes	0.198	0.033	0.233	0.033	0.344	0.055	0.225	0.040	nonoptimal.

* Each element set at 0.25.
\# Primary element set at 0.7 and others 0.11.

Table 3.3. Optimization run for 20 bridges under scenario 1 (initial data)

		Element Translated NBI Rating					Element relative weights							
brkey	NumElem	BARECONCDECK	POURSEALJOINT	COMPRESSJOINT	CONCRAILING	InspNBIRating	w1	w2	w3	w4	CalcNBIRating	delta	SumWeights	
550048	3	7.8	7.6	0.0	9.0	8.0	0.25	0.25	0.25	0.25	6.1	1.89	1.00	
550049	3	7.8	7.5	0.0	9.0	8.0	0.25	0.25	0.25	0.25	6.1	1.91	1.00	
724288	3	7.8	5.0	0.0	8.5	7.0	0.25	0.25	0.25	0.25	5.3	1.67	1.00	
770611	3	9.0	6.0	0.0	9.0	8.0	0.25	0.25	0.25	0.25	6.0	1.99	1.00	
755821	3	9.0	9.0	0.0	9.0	9.0	0.25	0.25	0.25	0.25	6.8	2.25	1.00	
756039	3	9.0	0.0	9.0	9.0	9.0	0.25	0.25	0.25	0.25	6.8	2.25	1.00	
870991	3	9.0	9.0	0.0	9.0	9.0	0.25	0.25	0.25	0.25	6.8	2.25	1.00	
870992	3	9.0	9.0	0.0	9.0	9.0	0.25	0.25	0.25	0.25	6.8	2.25	1.00	
870993	3	9.0	9.0	0.0	9.0	9.0	0.25	0.25	0.25	0.25	6.8	2.25	1.00	
870994	3	9.0	9.0	0.0	9.0	9.0	0.25	0.25	0.25	0.25	6.8	2.25	1.00	
874642	3	9.0	9.0	0.0	9.0	9.0	0.25	0.25	0.25	0.25	6.8	2.25	1.00	
874646	3	9.0	9.0	0.0	9.0	9.0	0.25	0.25	0.25	0.25	6.8	2.25	1.00	
874647	3	9.0	9.0	0.0	9.0	9.0	0.25	0.25	0.25	0.25	6.8	2.25	1.00	
920200	3	9.0	9.0	0.0	9.0	9.0	0.25	0.25	0.25	0.25	6.8	2.25	1.00	
930530	3	9.0	9.0	0.0	9.0	9.0	0.25	0.25	0.25	0.25	6.8	2.25	1.00	
930504	3	9.0	9.0	0.0	9.0	9.0	0.25	0.25	0.25	0.25	6.7	2.26	1.00	
930519	3	9.0	8.9	0.0	9.0	9.0	0.25	0.25	0.25	0.25	6.7	2.26	1.00	
930520	3	9.0	8.9	0.0	9.0	9.0	0.25	0.25	0.25	0.25	6.7	2.28	1.00	
900108	3	9.0	7.4	0.0	7.5	8.0	0.25	0.25	0.25	0.25	6.0	2.03	1.00	
500117	3	7.8	0.0	7.0	9.0	8.0	0.25	0.25	0.25	0.25	6.0	2.05	1.00	43.08

Table 3.4. Optimization run for 20 bridges under scenario 1 (final results)

		Element Translated NBI Rating					Element relative weights						
brkey	NumElem	BARECONCDECK	POURSEALJOINT	COMPRESSJOINT	CONCRAILING	InspNBIRating	w1	w2	w3	w4	CalcNBIRating	delta	SumWeights
550048	3	7.8	7.6	0.0	9.0	8.0	0.45	0.25	0.01	0.29	8.0	0.00	1.00
550049	3	7.8	7.5	0.0	9.0	8.0	0.46	0.24	0.01	0.29	8.0	0.00	1.00
724288	3	7.8	5.0	0.0	8.5	7.0	0.49	0.18	0.06	0.27	7.0	0.00	1.00
770611	3	9.0	6.0	0.0	9.0	8.0	0.52	0.18	0.05	0.25	8.0	0.00	1.00
755821	3	9.0	9.0	0.0	9.0	9.0	0.50	0.25	0.00	0.25	9.0	0.00	1.00
756039	3	9.0	0.0	9.0	9.0	9.0	0.50	0.00	0.25	0.25	9.0	0.00	1.00
870991	3	9.0	9.0	0.0	9.0	9.0	0.50	0.25	0.00	0.25	9.0	0.00	1.00
870992	3	9.0	9.0	0.0	9.0	9.0	0.50	0.25	0.00	0.25	9.0	0.00	1.00
870993	3	9.0	9.0	0.0	9.0	9.0	0.50	0.25	0.00	0.25	9.0	0.00	1.00

Table 3.5. Optimization run for 20 bridges under scenario 2 (final results)

		Element Translated NBI Rating					Element relative weights							
brkey	NumElem	BARECONCDECK	POURSEALJOINT	COMPRESSJOINT	CONCRAILING	InspNBIRating	w1	w2	w3	w4	CalcNBIRating	delta	SumWeights	
550048	3	7.8	7.6	0.0	9.0	8.0	0.70	0.00	0.00	0.17	7.0	1.04	0.87	
550049	3	7.8	7.5	0.0	9.0	8.0	0.70	0.00	0.00	0.17	7.0	1.03	0.87	
724288	3	7.8	5.0	0.0	8.5	7.0	0.70	0.00	0.08	0.13	6.6	0.44	0.91	
770611	3	9.0	6.0	0.0	9.0	8.0	0.70	0.00	0.00	0.13	7.5	0.54	0.83	
755821	3	9.0	9.0	0.0	9.0	9.0	0.70	0.15	0.00	0.00	7.7	1.35	0.85	
756039	3	9.0	0.0	9.0	9.0	9.0	0.70	0.00	0.15	0.00	7.7	1.35	0.85	
870991	3	9.0	9.0	0.0	9.0	9.0	0.70	0.15	0.00	0.00	7.7	1.35	0.85	
870992	3	9.0	9.0	0.0	9.0	9.0	0.70	0.15	0.00	0.00	7.7	1.35	0.85	
870993	3	9.0	9.0	0.0	9.0	9.0	0.70	0.15	0.00	0.00	7.7	1.35	0.85	
870994	3	9.0	9.0	0.0	9.0	9.0	0.70	0.15	0.00	0.00	7.7	1.35	0.85	
874642	3	9.0	9.0	0.0	9.0	9.0	0.70	0.15	0.00	0.00	7.7	1.35	0.85	
874646	3	9.0	9.0	0.0	9.0	9.0	0.70	0.15	0.00	0.00	7.7	1.35	0.85	
874647	3	9.0	9.0	0.0	9.0	9.0	0.70	0.15	0.00	0.00	7.7	1.35	0.85	
920200	3	9.0	9.0	0.0	9.0	9.0	0.70	0.15	0.00	0.00	7.7	1.35	0.85	
930530	3	9.0	9.0	0.0	9.0	9.0	0.70	0.15	0.00	0.00	7.7	1.35	0.85	
930504	3	9.0	9.0	0.0	9.0	9.0	0.70	0.15	0.00	0.15	9.0	0.00	1.00	
930519	3	9.0	8.9	0.0	9.0	9.0	0.70	0.00	0.00	0.15	7.7	1.34	0.85	
930520	3	9.0	8.9	0.0	9.0	9.0	0.70	0.00	0.00	0.15	7.7	1.33	0.85	
900108	3	9.0	7.4	0.0	7.5	8.0	0.73	0.00	0.00	0.00	6.6	1.41	0.73	
500117	3	7.8	0.0	7.0	9.0	8.0	0.70	0.00	0.00	0.18	7.1	0.94	0.88	22.92

Table 3.6. Optimization run for 20 bridges under scenario 3 (final results)

		Element Translated NBI Rating					Element relative weights							
brkey	NumElem	BARECONCDECK	POURSEALJOINT	COMPRESSJOINT	CONCRAILING	InspNBIRating	w1	w2	w3	w4	CalcNBIRating	delta	SumWeights	
550048	3	7.8	7.6	0.0	9.0	8.0	0.70	0.12	0.00	0.18	8.0	0.00	1.00	
550049	3	7.8	7.5	0.0	9.0	8.0	0.70	0.11	0.00	0.19	8.0	0.00	1.00	
724288	3	7.8	5.0	0.0	8.5	7.0	0.71	0.09	0.08	0.12	7.0	0.00	1.00	
770611	3	9.0	6.0	0.0	9.0	8.0	0.70	0.10	0.08	0.12	8.0	0.00	1.00	
755821	3	9.0	9.0	0.0	9.0	9.0	0.70	0.20	0.00	0.10	9.0	0.00	1.00	
756039	3	9.0	0.0	9.0	9.0	9.0	0.73	0.00	0.14	0.14	9.0	0.00	1.00	
870991	3	9.0	9.0	0.0	9.0	9.0	0.70	0.20	0.00	0.10	9.0	0.00	1.00	
870992	3	9.0	9.0	0.0	9.0	9.0	0.70	0.20	0.00	0.10	9.0	0.00	1.00	
870993	3	9.0	9.0	0.0	9.0	9.0	0.70	0.20	0.00	0.10	9.0	0.00	1.00	
870994	3	9.0	9.0	0.0	9.0	9.0	0.70	0.20	0.00	0.10	9.0	0.00	1.00	
874642	3	9.0	9.0	0.0	9.0	9.0	0.70	0.20	0.00	0.10	9.0	0.00	1.00	
874646	3	9.0	9.0	0.0	9.0	9.0	0.70	0.20	0.00	0.10	9.0	0.00	1.00	
874647	3	9.0	9.0	0.0	9.0	9.0	0.70	0.20	0.00	0.10	9.0	0.00	1.00	
920200	3	9.0	9.0	0.0	9.0	9.0	0.70	0.20	0.00	0.10	9.0	0.00	1.00	
930530	3	9.0	9.0	0.0	9.0	9.0	0.70	0.20	0.00	0.10	9.0	0.00	1.00	
930504	3	9.0	9.0	0.0	9.0	9.0	1.00	0.00	0.00	0.00	9.0	0.00	1.00	
930519	3	9.0	8.9	0.0	9.0	9.0	0.72	0.00	0.00	0.28	9.0	0.00	1.00	
930520	3	9.0	8.9	0.0	9.0	9.0	0.70	0.00	0.00	0.30	9.0	0.00	1.00	
900108	3	9.0	7.4	0.0	7.5	8.0	0.70	0.12	0.07	0.10	8.0	0.00	1.00	
500117	3	7.8	0.0	7.0	9.0	8.0	0.71	0.00	0.07	0.22	8.0	0.00	1.00	0.00

Table 3.7. Optimization run for 20 bridges under scenario 4 (final results)

		Element Translated NBI Rating					Element relative weights						
brkey	NumElem	BARECONCDECK	POURSEALJOINT	COMPRESSJOINT	CONCRAILING	InspNBIRating	w1	w2	w3	w4	CalcNBIRating	delta	SumWeights
724148	3	7.8	5.0	0.0	7.5	7.0	0.56	0.17	0.03	0.24	7.0	0.00	1.00
724359	3	7.8	5.0	0.0	7.5	7.0	0.56	0.17	0.03	0.24	7.0	0.00	1.00
724150	3	7.8	5.0	0.0	7.4	7.0	0.56	0.17	0.03	0.24	7.0	0.00	1.00
860423	3	9.0	0.0	5.0	9.0	8.0	0.55	0.04	0.16	0.25	8.0	0.00	1.00
170107	3	9.0	5.0	0.0	9.0	8.0	0.55	0.16	0.04	0.25	8.0	0.00	1.00
860218	3	9.0	0.0	5.0	9.0	8.0	0.55	0.04	0.16	0.25	8.0	0.00	1.00
860236	3	9.0	0.0	5.0	9.0	8.0	0.55	0.04	0.16	0.25	8.0	0.00	1.00
860383	3	9.0	0.0	5.0	9.0	8.0	0.55	0.04	0.16	0.25	8.0	0.00	1.00
860413	3	9.0	0.0	5.0	9.0	8.0	0.55	0.04	0.16	0.25	8.0	0.00	1.00
860414	3	9.0	0.0	5.0	9.0	8.0	0.55	0.04	0.16	0.25	8.0	0.00	1.00

Table 3.8. Optimization run for 20 bridges under scenario 5 (final results)

		Element Translated NBI Rating					Element relative weights							
brkey	NumElem	BARECONCDECK	POURSEALJOINT	COMPRESSJOINT	CONCRAILING	InspNBIRating	w1	w2	w3	w4	CalcNBIRating	delta	SumWeights	
724148	3	7.8	5.0	0.0	7.5	7.0	0.74	0.09	0.07	0.10	7.0	0.00	1.00	
724359	3	7.8	5.0	0.0	7.5	7.0	0.74	0.09	0.07	0.10	7.0	0.00	1.00	
724150	3	7.8	5.0	0.0	7.4	7.0	0.74	0.09	0.07	0.10	7.0	0.00	1.00	
860423	3	9.0	0.0	5.0	9.0	8.0	0.71	0.06	0.11	0.11	8.0	0.00	1.00	
170107	3	9.0	5.0	0.0	9.0	8.0	0.73	0.09	0.07	0.11	8.0	0.00	1.00	
860218	3	9.0	0.0	5.0	9.0	8.0	0.71	0.06	0.11	0.11	8.0	0.00	1.00	
860236	3	9.0	0.0	5.0	9.0	8.0	0.71	0.06	0.11	0.11	8.0	0.00	1.00	
860383	3	9.0	0.0	5.0	9.0	8.0	0.71	0.06	0.11	0.11	8.0	0.00	1.00	
860413	3	9.0	0.0	5.0	9.0	8.0	0.71	0.06	0.11	0.11	8.0	0.00	1.00	
860414	3	9.0	0.0	5.0	9.0	8.0	0.71	0.06	0.11	0.11	8.0	0.00	1.00	
860424	3	9.0	0.0	5.0	9.0	8.0	0.71	0.06	0.11	0.11	8.0	0.00	1.00	
860522	3	9.0	0.0	5.0	9.0	8.0	0.71	0.06	0.11	0.11	8.0	0.00	1.00	
860573	3	9.0	0.0	5.0	9.0	8.0	0.71	0.06	0.11	0.11	8.0	0.00	1.00	
870545	3	9.0	5.0	0.0	9.0	8.0	0.73	0.09	0.07	0.11	8.0	0.00	1.00	
930189	3	9.0	0.0	5.0	9.0	8.0	0.71	0.06	0.11	0.11	8.0	0.00	1.00	
930495	3	9.0	8.0	0.0	9.0	9.0	0.86	0.00	0.00	0.14	9.0	0.00	1.00	
870555	3	9.0	5.0	0.0	9.0	8.0	0.73	0.09	0.07	0.11	8.0	0.00	1.00	
930201	3	9.0	0.0	5.0	9.0	8.0	0.71	0.06	0.11	0.11	8.0	0.00	1.00	
930496	3	9.0	7.0	0.0	9.0	9.0	0.90	0.00	0.00	0.10	9.0	0.00	1.00	
034132	3	7.8	0.0	5.0	9.0	8.0	0.83	0.00	0.00	0.17	8.0	0.00	1.00	0.00

Table 3.9. Optimization run for 20 bridges under scenario 6 (final results)

		Element Translated NBI Rating					Element relative weights							
brkey	NumElem	BARECONCDECK	POURSEALJOINT	COMPRESSJOINT	CONCRAILING	InspNBIRating	w1	w2	w3	w4	CalcNBIRating	delta	SumWeights	
105603	3	6.6	8.7	0.0	8.9	4.0	0.14	0.12	0.51	0.23	4.0	0.00	1.00	
700027	3	9.0	8.5	0.0	9.0	5.0	0.06	0.26	0.43	0.25	5.0	0.00	1.00	
920098	3	6.6	9.0	0.0	9.0	5.0	0.21	0.20	0.39	0.20	5.0	0.00	1.00	
904110	3	4.2	5.0	0.0	9.0	3.0	0.30	0.22	0.41	0.07	3.0	0.00	1.00	
750158	3	6.6	8.6	0.0	9.0	5.0	0.21	0.21	0.38	0.20	5.0	0.00	1.00	
870022	3	9.0	8.9	0.0	9.0	6.0	0.17	0.25	0.33	0.25	6.0	0.00	1.00	
550052	3	7.8	7.0	0.0	9.0	5.0	0.14	0.26	0.37	0.23	5.0	0.00	1.00	
170086	3	9.0	8.7	0.0	9.0	6.0	0.17	0.25	0.32	0.25	6.0	0.00	1.00	
750127	3	5.4	9.0	0.0	9.0	5.0	0.28	0.19	0.33	0.19	5.0	0.00	1.00	
170085	3	9.0	8.3	0.0	9.0	6.0	0.18	0.25	0.31	0.25	6.0	0.00	1.00	
164207	3	7.8	9.0	0.0	9.0	6.0	0.21	0.24	0.31	0.24	6.0	0.00	1.00	
470023	3	7.8	9.0	0.0	9.0	6.0	0.21	0.24	0.31	0.24	6.0	0.00	1.00	
480032	3	7.8	9.0	0.0	9.0	6.0	0.21	0.24	0.31	0.24	6.0	0.00	1.00	
480033	3	7.8	9.0	0.0	9.0	6.0	0.21	0.24	0.31	0.24	6.0	0.00	1.00	
550070	3	7.8	9.0	0.0	9.0	6.0	0.21	0.24	0.31	0.24	6.0	0.00	1.00	
460019	3	7.8	9.0	0.0	9.0	6.0	0.21	0.24	0.30	0.24	6.0	0.00	1.00	
750157	3	7.8	8.8	0.0	9.0	6.0	0.21	0.24	0.30	0.24	6.0	0.00	1.00	
464007	3	6.6	7.0	0.0	9.0	5.0	0.20	0.24	0.34	0.22	5.0	0.00	1.00	
750038	3	6.6	7.0	0.0	9.0	5.0	0.20	0.24	0.34	0.22	5.0	0.00	1.00	
160270	3	7.8	8.7	0.0	9.0	6.0	0.22	0.24	0.30	0.24	6.0	0.00	1.00	0.00

Table 3.10. Optimization run for 20 bridges under scenario 7 (final results)

		Element Translated NBI Rating					Element relative weights						
brkey	NumElem	BARECONCDECK	POURSEALJOINT	COMPRESSJOINT	CONCRAILING	InspNBIRating	w1	w2	w3	w4	CalcNBIRating	delta	SumWeights
105603	3	6.6	8.7	0.0	8.9	4.0	0.70	0.00	0.30	0.00	4.6	-0.62	1.00
700027	3	9.0	8.5	0.0	9.0	5.0	0.70	0.00	0.30	0.00	6.3	-1.30	1.00
920098	3	6.6	9.0	0.0	9.0	5.0	0.70	0.00	0.26	0.04	5.0	0.00	1.00
904110	3	4.2	5.0	0.0	9.0	3.0	0.70	0.01	0.29	0.00	3.0	0.00	1.00
750158	3	6.6	8.6	0.0	9.0	5.0	0.70	0.00	0.26	0.04	5.0	0.00	1.00
870022	3	9.0	8.9	0.0	9.0	6.0	0.70	0.00	0.30	0.00	6.3	-0.30	1.00
550052	3	7.8	7.0	0.0	9.0	5.0	0.70	0.00	0.30	0.00	5.5	-0.46	1.00
170086	3	9.0	8.7	0.0	9.0	6.0	0.70	0.00	0.30	0.00	6.3	-0.30	1.00
750127	3	5.4	9.0	0.0	9.0	5.0	0.72	0.02	0.16	0.10	5.0	0.00	1.00

3.3. Operation of the NBI Translator Program

A computer program, the NBI Translator Program, was written on two programming platforms in the Microsoft Windows Operating System, to implement the methodology described above. One is a standalone program while the other is embedded within the Microsoft Excel Spreadsheet program. The standalone program was written in the Microsoft Visual Basic Programming Language. Using tables from the Microsoft Access Database for input/output data operations, the process is briefly described in the following paragraphs. Some sample screen shots of both forms of the program running are shown in Figures 3.6 and 3.7. The basic operations within the NBI Translator Program are shown in the flow charts in Figures 3.4 and 3.5, with Figure 3.5 showing more details on the data tables and relationship between them. The structure of database tables is shown in Tables 3.11 to 3.16, including the source of each field on the tables.

The database for the program is housed in a Microsoft Access database file called *translate.mdb*. First, the Pontis element condition data table *eleminsp* for the bridge inventory is opened in the MS Access format, reduced to the only the needed fields, and renamed in this program as the database table *ElementData.* Also needed is a *FactorsBridge* table with pertinent information on bridge elements' suggested bridge component or category (deck, superstructure, substructure, culvert, smart flags, etc.), including element weighting factors, indicating the importance of the element in that bridge component (varies from 0 to 100), and the Pontis field *statecnt*, a count of condition states for each element.

A working file *elemdatafile* is then created for the entire inventory, to store for each element, the bridge component, the condition index (varies from 0 to 1), and a computed NBI rating equivalent (varies from 0 to 9). Using the *BridgeComponent* field, a "smartflags" table (*elemdatafileSmartflags*) is created from the *elemdatafile* table, as well as working files for each bridge component, i.e., tables *elemdatafiledeck, elemdatafilesuperstructure, elemdatafilesubstructure, and elemdatafileculvert.* The smart flags are assigned to the respective bridge components as follows: element numbers 358 and 359 are smart flags for decks; element numbers 356, 357, 362, 363, 370 are assigned to the bridge superstructure elements; and element numbers 360, 361, and 369 are smart flags for substructures. A condition index is also computed for the smart flags data; for a bridge element with multiple smart flags, an average smart flag index is computed. The bridge element condition index and NBI ratings are modified with the smart flag index, where applicable, using a direct multiplication of the index (0 to 1) to indicate the rate of deterioration.

At each specific bridge component, the number of elements is computed, as well as a normalized set of weight factors for the elements comprising the component. A weighted average of the elements' NBI rating is then computed as the translated NBI rating of the bridge component. The operation is done on a component basis, i.e., user selects deck, superstructure, substructure, or culvert component to be translated. One of the available options is the comparison of the translated ratings to the actual field-inspected NBI ratings, with a statistic computed -- the average mean of the square of the differences. Based on Florida's bridge condition data for 2007 and 2008 inspections, some regression coefficients were established for relating the actual inspected NBI ratings to the translated component ratings. These coefficients were found to be useful in further improving the accuracy in the translation program, as explained later in this report.

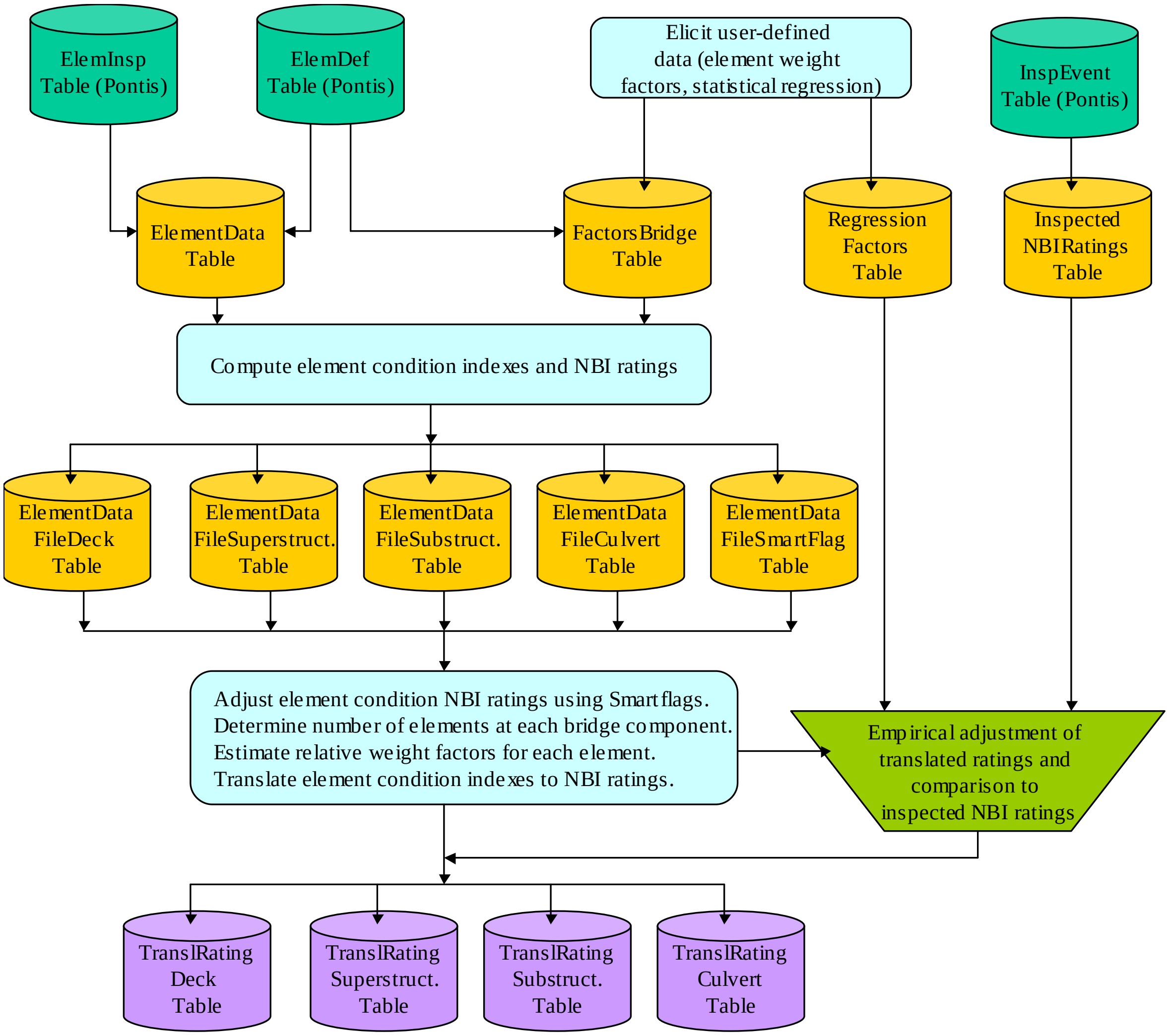


Figure 3.4. Overall flow chart for operations within the NBI Translator Program

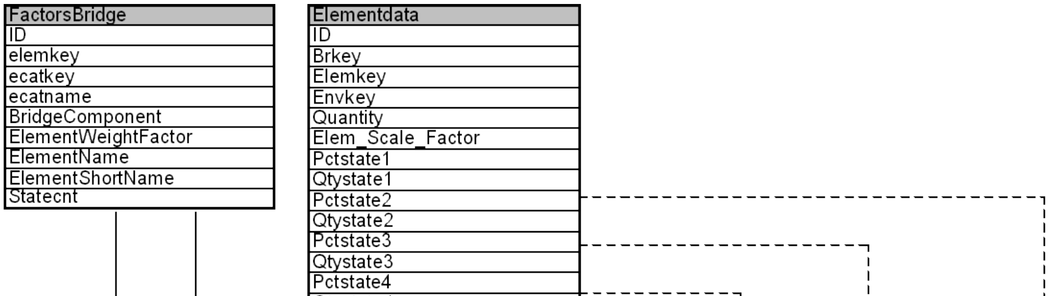


Figure 3.5. Schematic diagram of data flow and table relationships in the NBI Translator Program

Table 3.11. Table definitions for basic data input

Table Name	Fields	Source
Elementdata	ID	MS Access
	Brkey	Pontis
	Elemkey	Pontis
	Envkey	Pontis
	Quantity	Pontis
	Elem_Scale_Factor	Pontis
	Pctstate1	Pontis
	Qtystate1	Pontis
	Pctstate2	Pontis
	Qtystate2	Pontis
	Pctstate3	Pontis
	Qtystate3	Pontis
	Pctstate4	Pontis
	Qtystate4	Pontis
	Pctstate5	Pontis
	Qtystate5	Pontis
FactorsBridge	ID	MS Access
	elemkey	Pontis
	ecatkey	Pontis
	ecatname	Pontis
	BridgeComponent	Pontis/User-Defined
	ElementWeightFactor	User-Defined
	ElementName	Pontis
	ElementShortName	Pontis
	Statecnt	Pontis
NBIInspRatingDeckAge	ID	MS Access
	brkey	Pontis
	Rating	Pontis
	Yearbuilt	Pontis
NBIInspRatingSuperstructureAge	ID	MS Access
	brkey	Pontis
	Rating	Pontis
	Yearbuilt	Pontis
NBIInspRatingsubstructureAge	ID	MS Access
	brkey	Pontis
	Rating	Pontis
	Yearbuilt	Pontis
NBIInspRatingCulvertAge	ID	MS Access
	brkey	Pontis
	Rating	Pontis
	Yearbuilt	Pontis
RegressionFactors	ID	MS Access
	BridgeComponent	Pontis/User-Defined
	ConstantCoefficient	User-Defined
	SlopeCoefficient	User-Defined
	AgeTrigger	User-Defined

Table 3.12. Table definitions for program-generated data (bridge components data input and smart flags)

Table Name	Fields	Source
elemdatadeck	ID brkey elemkey ecatkey ecatname BridgeComponent ElementWeightFactor ConditionIndex NBIRating	MS Access Pontis Pontis Pontis Pontis Pontis/User-Defined User-Defined Program Program
elemdatasuperstructure	ID brkey elemkey ecatkey ecatname BridgeComponent ElementWeightFactor ConditionIndex NBIRating	MS Access Pontis Pontis Pontis Pontis Pontis/User-Defined User-Defined Program Program
elemdatasubstructure	ID brkey elemkey ecatkey ecatname BridgeComponent ElementWeightFactor ConditionIndex NBIRating	MS Access Pontis Pontis Pontis Pontis Pontis/User-Defined User-Defined Program Program
elemdataculvert	ID brkey elemkey ecatkey ecatname BridgeComponent ElementWeightFactor ConditionIndex NBIRating	MS Access Pontis Pontis Pontis Pontis Pontis/User-Defined User-Defined Program Program
elemdatasmartflags	ID brkey elemkey ecatkey ecatname BridgeComponent ElementWeightFactor ConditionIndex NBIRating	MS Access Pontis Pontis Pontis Pontis Pontis/User-Defined User-Defined Program Program

Table 3.13. Table definitions for Program-generated data (bridge decks translation)

Table Name	Fields	Source
nbinewdeck	ID brkey NumElements SumWF	MS Access Pontis Program Program
smartflgsnewdeck	ID brkey NumFlags AvgSmartFlgCond SumSmartFlgs	MS Access Pontis Program Program Program
smartflgsxdeck	ID brkey elemkey SmartFlagCondIndex NBIRating	MS Access Pontis Pontis/User-Defined Program Program
nbitransdeck	ID brkey BridgeComponent TranslRating	MS Access Pontis Pontis/User-Defined Program
NBITransCompareDeck	ID brkey BridgeComponent TranslRating InspNBIRating ModTranslRating OrigAbsDiff ModAbsDiff InspYear	MS Access Pontis Pontis/User-Defined Program Program Program Program Program Pontis

Table 3.14. Table definitions for Program-generated data (bridge superstructures translation)

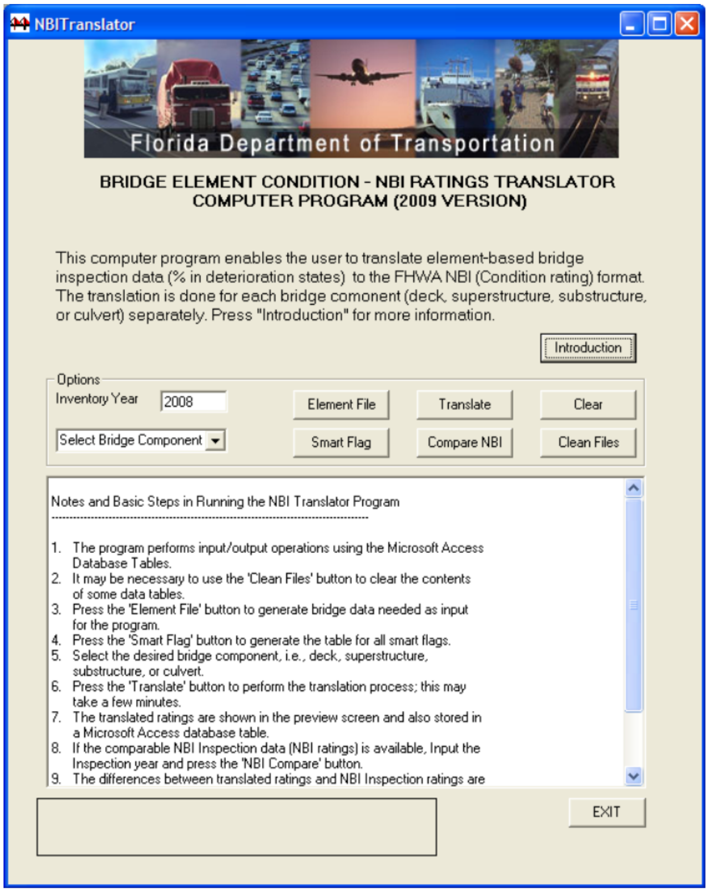
Table Name	Fields	Source
nbinewsuperstructure	ID brkey NumElements SumWF	MS Access Pontis Program Program
smartflgsnewsuperstructure	ID brkey NumFlags AvgSmartFlgCond SumSmartFlgs	MS Access Pontis Program Program Program
smartflgsxsuperstructure	ID brkey elemkey SmartFlagCondIndex NBIRating	MS Access Pontis Pontis Program Program
nbitranssuperstructure	ID brkey BridgeComponent TranslRating	MS Access Pontis Pontis/User-Defined Program
NBITransComparesuperstructure	ID brkey BridgeComponent TranslRating InspNBIRating ModTranslRating OrigAbsDiff ModAbsDiff InspYear	MS Access Pontis Pontis/User-Defined Program Program Program Program Program Pontis

Table 3.15. Table definitions for Program-generated data (bridge substructures translation)

Table Name	Fields	Source
nbinewsubstructure	ID brkey NumElements SumWF	MS Access Pontis Program Program
smartflgsnewsubstructure	ID brkey NumFlags AvgSmartFlgCond SumSmartFlgs	MS Access Pontis Program Program Program
smartflgsxsubstructure	ID brkey elemkey SmartFlagCondIndex NBIRating	MS Access Pontis Pontis/User-Defined Program Program
nbitranssubstructure	ID brkey BridgeComponent TranslRating	MS Access Pontis Pontis/User-Defined Program
NBITransCompareSubstructure	ID brkey BridgeComponent TranslRating InspNBIRating ModTranslRating OrigAbsDiff ModAbsDiff InspYear	MS Access Pontis Pontis/User-Defined Program Program Program Program Program Pontis

Table 3.16. Table definitions for Program-generated data (culverts translation)

Table Name	Fields	Source
nbinewculvert	ID brkey NumElements SumWF	MS Access Pontis Program Program
smartflgsnewculvert	ID brkey NumFlags AvgSmartFlgCond SumSmartFlgs	MS Access Pontis Program Program Program
smartflgsxculvert	ID brkey elemkey SmartFlagCondIndex NBIRating	MS Access Pontis Pontis/User-Defined Program Program
nbitransculvert	ID brkey BridgeComponent TranslRating	MS Access Pontis Pontis/User-Defined Program
NBITransCompareCulvert	ID brkey BridgeComponent TranslRating InspNBIRating ModTranslRating OrigAbsDiff ModAbsDiff InspYear	MS Access Pontis Pontis/User-Defined Program Program Program Program Program Pontis



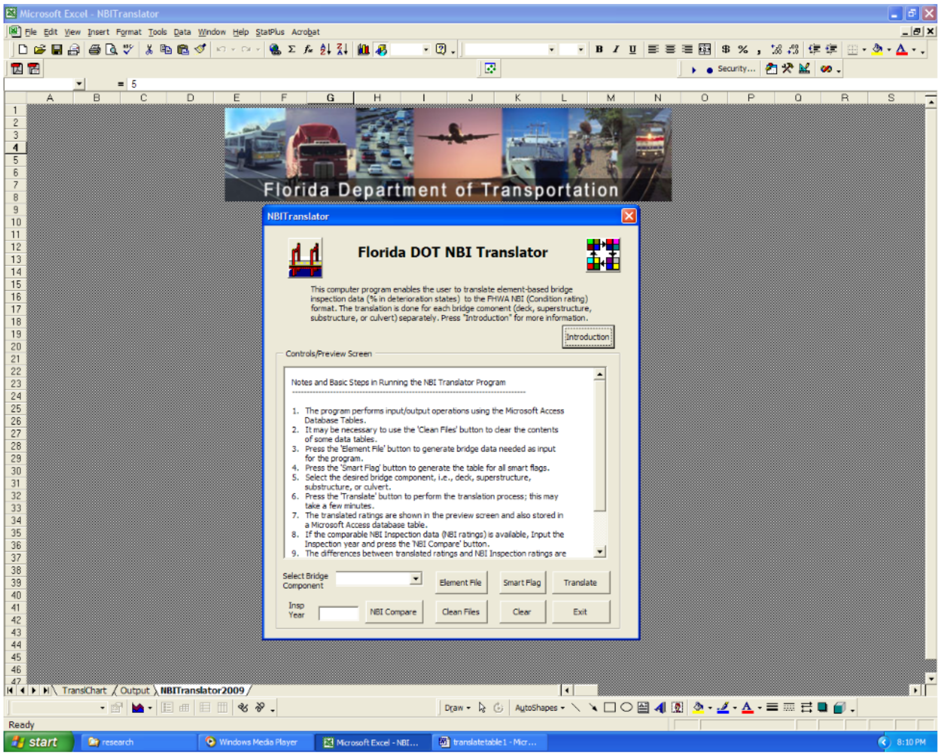
BRIDGE ELEMENT CONDITION - NBI RATINGS TRANSLATOR
COMPUTER PROGRAM (2009 VERSION)

This computer program enables the user to translate element-based bridge inspection data (% in deterioration states) to the FHWA NBI (Condition rating) format. The translation is done for each bridge comonent (deck, superstructure, substructure, or culvert) separately. Press "Introduction" for more information.

Notes and Basic Steps in Running the NBI Translator Program

1. The program performs input/output operations using the Microsoft Access Database Tables.
2. It may be necessary to use the 'Clean Files' button to clear the contents of some data tables.
3. Press the 'Element File' button to generate bridge data needed as input for the program.
4. Press the 'Smart Flag' button to generate the table for all smart flags.
5. Select the desired bridge component, i.e., deck, superstructure, substructure, or culvert.
6. Press the 'Translate' button to perform the translation process; this may take a few minutes.
7. The translated ratings are shown in the preview screen and also stored in a Microsoft Access database table.
8. If the comparable NBI Inspection data (NBI ratings) is available, Input the Inspection year and press the 'NBI Compare' button.
9. The differences between translated ratings and NBI Inspection ratings are

Figure 3.6. Sample screen shot of standalone Translator Program



Florida DOT NBI Translator

This computer program enables the user to translate element-based bridge inspection data (% in deterioration states) to the FHWA NBI (Condition rating) format. The translation is done for each bridge comonent (deck, superstructure, substructure, or culvert) separately. Press "Introduction" for more information.

Notes and Basic Steps in Running the NBI Translator Program

1. The program performs input/output operations using the Microsoft Access Database Tables.
2. It may be necessary to use the 'Clean Files' button to clear the contents of some data tables.
3. Press the 'Element File' button to generate bridge data needed as input for the program.
4. Press the 'Smart Flag' button to generate the table for all smart flags.
5. Select the desired bridge component, i.e., deck, superstructure, substructure, or culvert.
6. Press the 'Translate' button to perform the translation process; this may take a few minutes.
7. The translated ratings are shown in the preview screen and also stored in a Microsoft Access database table.
8. If the comparable NBI Inspection data (NBI ratings) is available, Input the Inspection year and press the 'NBI Compare' button.
9. The differences between translated ratings and NBI Inspection ratings are

Figure 3.7. Sample screen shot of Microsoft Excel-based Translator Program

3.4. Results

The Translator Program was applied to FDOT bridge condition records for 2007 and 2008 inspection years. The accuracy of the translation was estimated by comparison of the translated ratings to values from NBI ratings of the same bridges obtained through a simultaneous inspection using both element and NBI inspection methods. For each inspected NBI rating, the values of translated ratings for various bridges are evaluated in terms of the following statistics estimated: mean, standard deviation, and mean of the absolute difference from inspected ratings.

The initial run of the Translator Program was on the entire bridge inventory, i.e., including both state and non-state maintained bridges. Due to relatively large errors observed on this run, a second run using only state-maintained bridges (NBI owner codes 1,31, and 33) was done to produce fewer errors. Thus primarily the translated results from the state-maintained bridges are discussed in this report. During the development of the program and between runs, bridges showing large errors of translation were reviewed in detail to see the inconsistencies between the element inspection data and the inspected NBI ratings. Some of these observations are summarized in Tables 3.17 and 3.18 for superstructures and substructures. While some differences cannot be explained, it was observed that on bridges with slabs and no traditional deck element, it is necessary to consider the slab as both deck and superstructure components on the bridge. It is also suspected that on bridge components with many elements, the NBI rating inspector may be biased by the condition of a secondary element. Thus, for example, a badly deteriorated bearing (secondary element) on a good girder (primary element) superstructure system may strongly influence the inspector to assign a poor value of overall NBI rating for the component.

An investigation was conducted to see if there was any the relationship between the prediction errors (AbsDiff) and the bridge attributes such as structural type, maximum bridge span, bridge length, material type, and deck area. The correlation coefficients were found to be low values implying insignificant relationship. Also reviewed was the influence if any, that the condition of substructures associated with culverts, has on the overall bridge NBI rating of the culvert. This was found to be insignificant.

For some categories of bridge components, it was necessary to further adjust the translated ratings, in order to reduce the translation errors. Basically regression equations were developed, relating the field-inspected NBI component ratings to the translated ratings. These equations 3.16 to 3.19 shown below, were used to modify the original translated ratings, using the regression coefficients stored in the *RegressionFactors* table, resulting in new set of translated ratings.

decks: $R^1 = 4.6317 + 0.3333R$ (3.16)

superstructures: $R^1 = 4.9114 + 0.2785R$ (3.17)

substructures: $R^1 = 1.3863 + 0.6771R$ (3.18)

culverts: $R^1 = 5.267 + 0.2236R$ (3.19)

where,

R^1 = the modified translated NBI rating of bridge component (deck, superstructure, substructure, or culvert), with $2 \leq R^1 \leq 9$.

R = the original translated NBI rating of bridge component (deck, superstructure, substructure, or culvert), with $2 \leq R \leq 9$.

Table 3.17. Review of selected translated results for superstructures

brkey	elemkey	Elem Weight Factor	Elem Cond. Index	Elem NBI Rating	Transl. NBI Rating	Insp. NBI Rating	Comments
010035	109	100	1.00	8.92	7.6	7	The main superstructure element (no. 109 P/S Conc Open Girder/Beam) is in excellent condition but the secondary element (no. 310 Elastomeric Bearing) is in fair/poor condition. The translated rating properly accounts for the weighted aggregation of the overall condition index, though not perfectly.
	310	50	0.52	4.90			
100522	398	50	0.10	2.45	2.5 (6.8)	7	Bridge had only one superstructure element (No. 110 Drain. Syst Other) in an initial run; with element no. 38, concrete slab, categorized only as deck. Making elem. no. 38 a superstructure improved the translated superstructure rating to 6.8.
120064	107	100	0.93	8.29	7.6	4	Element nos. 310 Elastomeric Bearing and 313 Fixed Bearing are in fair/poor condition. Element nos. 107 Painted Steel Open Girder/Beam and 113 Painted Steel Stringer are in fair condition. Other elements 109 P/S Conc Open Girder/Beam, 152 Painted Steel Floor Beam, and 311 Enclosed/Concealed Bearing, are in excellent condition. The NBI inspection here may be too subjective because there are many elements inspected and the worst of these elements (bearings) may have biased the NBI rating of 4 (poor).
	109	100	1.00	8.92			
	113	50	0.65	5.92			
	152	50	0.84	7.42			
	310	50	0.52	4.90			
	311	50	0.90	8.03			
	313	50	0.52	4.90			
130104	109	100	0.99	8.85	8.8	5	Elements no. 109 P/S Conc Open Girder/Beam and no. 310 Elastomeric Bearing are both in excellent condition according to element inspection. But NBI rating indicates otherwise.
	310	50	0.99	8.81			
520004	110	100	0.99	8.87	8.9	3	Bridge has only one element (No. 110 R/Conc Open Girder)
604004	111	100	0.95	8.48	9	5	Bridge has only one element (No. 111 Timber Open Girder) inspected (recorded) as in excellent condition. This is a major superstructure element. Possible cause here may be subjectivity in the NBI inspection rating or inadequate number of elements inspected. Also this is an off-system bridge.
750319	109	100	1.00	8.92	8.9	7	Elements no. 109 P/S Conc Open Girder/Beam and no. 310 Elastomeric Bearing are both in excellent condition according to element inspection. But NBI rating indicates otherwise. Bridge has element no. 98, Concrete Deck on Precast Deck Panels, which was classified as a superstructure; elem 98 is in poor condition.
	310	50	1.00	8.87			
750398	109	100	0.99	8.87	9.0	6	Elements no. 109 P/S Conc Open Girder/Beam and no. 310 Elastomeric Bearing are both in excellent condition according to element inspection. But NBI rating indicates otherwise.
	310	50	1.00	8.87			

Table 3.17. Review of selected translated results for superstructures (continued)

780076	109	100	1.00	8.88	8.9	5	Elements no. 109 P/S Conc Open Girder/Beam and no. 310 Elastomeric Bearing are both in excellent condition according to element inspection. But NBI rating indicates otherwise. Bridge has element no. 12, Concrete Deck – Bare, in a poor condition.
	310	50	1.00	8.87			
860158	310	50	1.00	8.87	9.0 (8.0)	7	Elem.no. 310 Elastomeric Bearing is in excellent condition according to element inspection. In an initial run, this was only the superstructure element, yielding a translated rating of 8.9. But after including the bridge element no. 99 Prestressed Concrete Slab (Sonovoid) in fair condition, as a superstructure element, the NBI rating is now 8.0.

Table 3.18. Review of selected translated results for substructures

brkey	elemkey	Elem. Weight Factor	Elem. Cond. Index	Elem NBI Rating	Transl. NBI Rating	Insp. NBI Rating	Comments
160273	204	100	0.88	7.79	8.5	7	Element no. 204 P/S Conc Column or Pile is in good condition while element no. 290 Channel is in good condition. Other elements are in excellent condition. The good condition NBI rating of 7 may have been based solely on Element nos. 204 and 290.
	215	100	1.00	8.92			
	234	100	0.99	8.83			
	290	20	0.60	5.51			
	394	50	1.00	8.92			
	396	50	1.00	8.92			
	475	100	0.97	8.61			
	478	100	0.96	8.53			
480213	207	100	0.93	8.27	8.8	4	The following elements are in excellent condition but the inspection shows NBI rating 4: 215 Reinforced Conc Abutment; 220 Pile Cap/Footing; 207 Hollow Core Pile; 234 Reinforced Conc Cap; 394 Abutment Slope Protection Reinforced Concrete; 290 Channel; 475 Wingwall/Retaining Wall Reinforced Concrete.
	215	100	1.00	8.92			
	220	100	1.00	8.92			
	234	100	0.99	8.85			
	290	20	1.00	8.92			
	394	50	1.00	8.92			
	475	100	1.00	8.92			
570054	205	100	1.00	8.92	7.9	5	Element nos. 220 Pile Cap/Footing and 290 Channel are the only ones in fair condition while other elements are in excellent condition. The fair condition of inspected NBI rating of 5 may have been based solely on Element no. 220.
	207	100	1.00	8.89			
	210	100	0.60	5.51			
	215	100	1.00	8.92			
	220	100	0.60	5.51			
	234	100	1.00	8.92			
	290	20	0.60	5.51			
	396	50	1.00	8.92			
	475	100	1.00	8.92			
700201	205	100	1.00	8.92	8.0	7	Element no. 210 Reinforced Conc Pier Wall is in fair/good condition. While nos. 290 Channel, and 478 Mechanically Stabilized Earth Wall are the only ones in fair condition. Other elements are in excellent or almost excellent condition. The good condition NBI rating of 7 may have been based solely on Element no. 210, with condition of Channel and MSE walls considered but given a lower weight.
	210	100	0.72	6.48			
	215	100	0.98	8.71			
	234	100	1.00	8.92			
	290	20	0.60	5.51			
	387	100	1.00	8.92			
	396	50	0.93	8.24			
	475	100	1.00	8.92			
	478	100	0.60	5.51			
920011	204	100	0.60	5.51	8.0	6	Element no. 204 P/S Conc Column or Pile is in fair condition while element no. 298 Pile Jacket without Cathodic Protection is in good condition. Other elements are in excellent condition. The fair condition of inspected NBI rating of 6 may have been based solely on Element nos. 204 and 298.
	215	100	1.00	8.92			
	234	100	1.00	8.90			
	290	20	1.00	8.92			
	298	100	0.83	7.35			
	396	50	1.00	8.92			
	475	100	1.00	8.92			

The regression models are shown in Figures 3.8 and 3.9 for bridge decks. The initial application of the regression coefficients did not produce good results for element condition data at inspected NBI ratings “9”; this is not unexpected given the linear regression equations and plots as shown in Figures 3.8 and 3.9. The regression models show lower values of predicted translated ratings for ratings higher than the inspected NBI rating “7” and higher predicted values for ratings lower than NBI rating “7.”

A review of the age distribution of bridge decks also shows, as expected that, most of the decks in rating 9 are new bridges. For the bridge decks inspected with both element and NBI inspections, in 2007, 52 decks were NBI-rated “9.” Of these 52 bridges, 49 or about 94 % of the decks were 5 or fewer years old. There were also three rehabilitated bridge decks included (aged 20, 40, and 55 years). For this reason, it seems statistically reasonable to exclude new bridges from the empirical modification of the original translated ratings using the regression models discussed earlier. In other words, age computed from the year the bridge was built, is used as a criterion in the Translator program (termed *AgeTrigger* in the *RegressionFactors* table).

While bridge inspectors do not consider age in their inspections, it was however observed that in translating the ratings, using the age as a criterion improved the accuracy of the translation on the overall. The summaries of the translated ratings are shown in Tables 3.19 to 3.26 and Figures 3.10 to 3.17. It could be observed that modification with regression coefficients significantly improved the average ratings and the absolute differences of the translated ratings, from the original translated (*mean origTranslated rating*) values to the new values (*mean regrTranslated ratings*) for all bridge components, especially for the NBI ratings greater than “6.” While this may sound like a concern, it should be noted that for every bridge component type and culvert considered, most bridges are in NBI ratings 7 or higher, with roughly about 90% for bridge decks, superstructures, and substructures, and about 80% for culverts. Overall the translation accuracy was not very good for bridge components or culverts in NBI ratings les than “5.” But given also that there are only fewer than about 5% of the bridges in the inventory with NBI condition ratings less than or equal to “5,” the results should be considered reasonably accurate for the overall bridge inventory.

In Tables 3.27 to 3.31 it could be seen that using rounded values of the translated ratings (to whole numbers as done in NBI scheme), exact translations were obtained for about half of the bridges analyzed. As mentioned earlier, the accuracy significantly improved for decks from original translation as shown in Table 3.27 (about 35% exact translations) to the modified translation shown in Table 3.28 (about 52% exact translations) when the regression factors are. In Table 3.28, it could be seen that using the regression-based translation, for bridge decks with inspected ratings of 7 and 9, about 64% and 85% respectively were translated (rounded) exactly as the inspected ratings. Similarly for bridge superstructures as shown in Table 3.29, the corresponding values are 90% and 100% respectively, while for substructures, the values are 87% and 97% respectively.

Using the plots shown in Figures 3.18 to 3.22, where the number of bridges at each point is expressed clearer, as size of the bubble, it can be seen that modification of the translation using the regression factors improves accuracy of the translation for bridge superstructures, substructures and culverts. Comparing Figures 3.18 and 3.19 illustrates the improvement in accuracy for bridge decks, especially for the bridge decks inspected at NBI rating of 7. Looking at Figures 3.19 to 3.21 for decks, superstructures, and substructures respectively, generally the translation ratings are reasonably accurate except for the inspected NBI rating 8 which has a good average translated rating but many of the translated ratings are either one above or below the inspected rating.

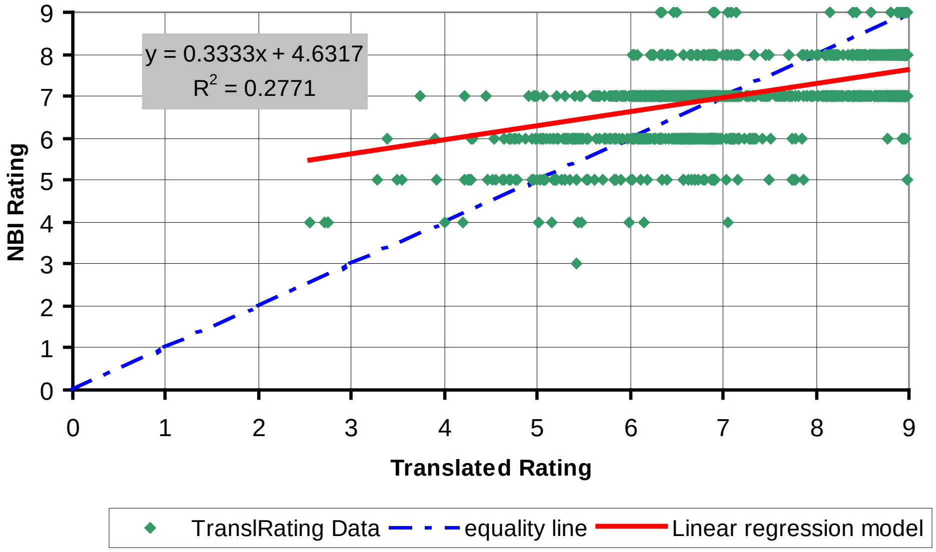


Figure 3.8. Relating translated to NBI ratings for decks inspected in 2007 on state-maintained bridges

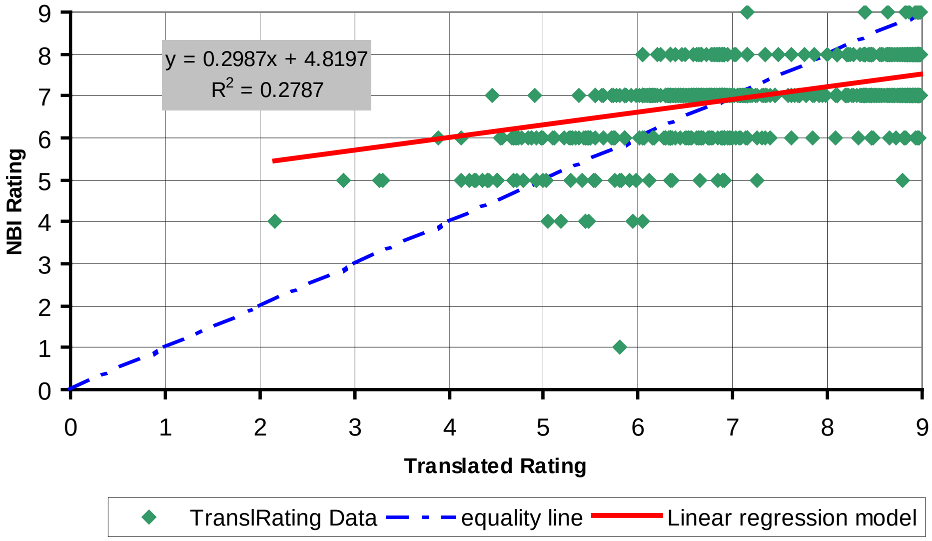


Figure 3.9. Relating translated to NBI ratings for decks inspected in 2008 on state-maintained bridges

Table 3.19. Summary of translation of bridge decks inspected in 2007.

Inspected NBIRating	mean origTranslated Rating	Stdev origTranslated Rating	mean origAbs Difference	mean regrTranslated Rating	Stdev regrTranslated Rating	mean regrAbs Difference	No. of Bridges	% of Bridges
4	4.8	1.29	1.23	6.1	0.50	2.15	13	0.5%
5	6.1	1.30	1.36	6.6	0.39	1.56	76	2.7%
6	6.6	1.03	0.94	6.7	0.28	0.74	287	10.2%
7	7.3	1.04	0.84	7.0	0.44	0.30	1933	68.6%
8	8.2	0.90	0.84	7.9	0.84	0.78	456	16.2%
9	8.4	0.92	0.64	8.2	1.00	0.78	51	1.8%

Table 3.20. Summary of translation of bridge decks inspected in 2008.

Inspected NBIRating	mean origTranslated Rating	Stdev origTranslated Rating	mean origAbs Difference	mean regrTranslated Rating	Stdev regrTranslated Rating	mean regrAbs Difference	No. of Bridges	% of Bridges
4	5.0	1.32	1.57	6.3	0.44	2.31	7	0.4%
5	5.2	1.20	0.94	6.4	0.40	1.38	39	2.1%
6	6.4	1.09	0.92	6.8	0.39	0.77	151	8.2%
7	7.6	1.09	0.98	7.3	0.59	0.43	1232	67.0%
8	8.5	0.78	0.84	8.0	0.80	0.74	383	20.8%
9	8.8	0.38	0.19	8.8	0.38	0.19	27	1.5%

Table 3.21. Summary of translation of bridge superstructures inspected in 2007.

Inspected NBIRating	mean origTranslated Rating	Stdev origTranslated Rating	mean origAbs Difference	mean regrTranslated Rating	Stdev regrTranslated Rating	mean regrAbs Difference	No. of Bridges	% of Bridges
4	5.6	1.81	1.95	6.5	0.50	2.46	15	0.5%
5	6.6	1.75	1.87	6.8	0.59	1.78	69	2.5%
6	7.1	1.54	1.63	6.9	0.46	0.91	205	7.3%
7	8.1	1.15	1.46	7.2	0.51	0.42	1697	60.6%
8	8.7	0.57	0.89	7.8	0.75	0.74	762	27.2%
9	8.5	1.14	0.47	8.5	1.14	1.14	53	1.9%

Table 3.22. Summary of translation of bridge superstructures inspected in 2008.

Inspected NBIRating	mean origTranslated Rating	Stdev origTranslated Rating	mean origAbs Difference	mean regrTranslated Rating	Stdev regrTranslated Rating	mean regrAbs Difference	No. of Bridges	% of Bridges
4	5.0	1.32	1.57	6.3	0.44	2.31	7	0.4%
5	5.2	1.20	0.94	6.4	0.40	1.38	39	2.1%
6	6.4	1.09	0.92	6.8	0.39	0.77	151	8.2%
7	7.6	1.09	0.98	7.3	0.59	0.43	1232	67.0%
8	8.5	0.78	0.84	8.0	0.80	0.74	383	20.8%
9	8.8	0.38	0.19	8.8	0.38	0.19	27	1.5%

Table 3.23. Summary of translation of bridge substructures inspected in 2007.

Inspected NBIRating	mean origTranslated Rating	Stdev origTranslated Rating	mean origAbs Difference	mean regrTranslated Rating	Stdev regrTranslated Rating	mean regrAbs Difference	No. of Bridges	% of Bridges
4	7.2	1.08	3.24	6.3	0.73	2.28	29	1.0%
5	7.5	0.93	2.52	6.5	0.63	1.48	57	2.0%
6	7.8	0.74	1.86	6.7	0.50	0.77	203	7.2%
7	8.6	0.45	1.60	7.3	0.48	0.41	1716	61.0%
8	8.8	0.19	0.82	7.9	0.73	0.72	748	26.6%
9	8.9	0.11	0.13	8.8	0.31	0.18	61	2.2%

Table 3.24. Summary of translation of bridge substructures inspected in 2008.

Inspected NBIRating	mean origTranslated Rating	Stdev origTranslated Rating	mean origAbs Difference	mean regrTranslated Rating	Stdev regrTranslated Rating	mean regrAbs Difference	No. of Bridges	% of Bridges
4	7.4	1.12	3.43	6.5	0.87	2.47	27	1.5%
5	7.3	0.94	2.35	6.4	0.64	1.38	38	2.1%
6	7.8	0.85	1.79	6.7	0.61	0.80	144	7.8%
7	8.5	0.51	1.58	7.3	0.54	0.45	1063	57.7%
8	8.8	0.24	0.81	7.9	0.77	0.75	537	29.2%
9	8.9	0.03	0.09	8.9	0.26	0.14	32	1.7%

Table 3.25. Summary of translation of bridge culverts inspected in 2007.

Inspected NBIRating	mean origTranslated Rating	Stdev origTranslated Rating	mean origAbs Difference	mean regrTranslated Rating	Stdev regrTranslated Rating	mean regrAbs Difference	No. of Bridges	% of Bridges
4	4.1	0.80	0.57	6.2	0.18	2.18	2	0.4%
5	4.5	1.08	1.07	6.3	0.24	1.27	22	4.0%
6	5.7	1.01	0.79	6.5	0.24	0.53	127	23.3%
7	6.9	1.58	1.51	6.9	0.55	0.44	357	65.4%
8	8.4	1.07	1.01	8.1	0.93	0.89	32	5.9%
9	8.8	0.18	0.15	8.6	0.72	0.37	6	1.1%

Table 3.26. Summary of translation of bridge culverts inspected in 2008.

Inspected NBIRating	mean origTranslated Rating	Stdev origTranslated Rating	mean origAbs Difference	mean regrTranslated Rating	Stdev regrTranslated Rating	mean regrAbs Difference	No. of Bridges	% of Bridges
4	3.5		0.48	6.1		2.05	1	0.3%
5	4.5	1.09	1.02	6.3	0.24	1.27	10	3.2%
6	5.8	1.21	0.95	6.6	0.37	0.59	62	19.7%
7	6.9	1.53	1.46	6.9	0.59	0.46	222	70.5%
8	8.7	0.78	0.94	8.0	0.92	0.88	19	6.0%
9	8.9		0.08	8.9		0.08	1	0.3%

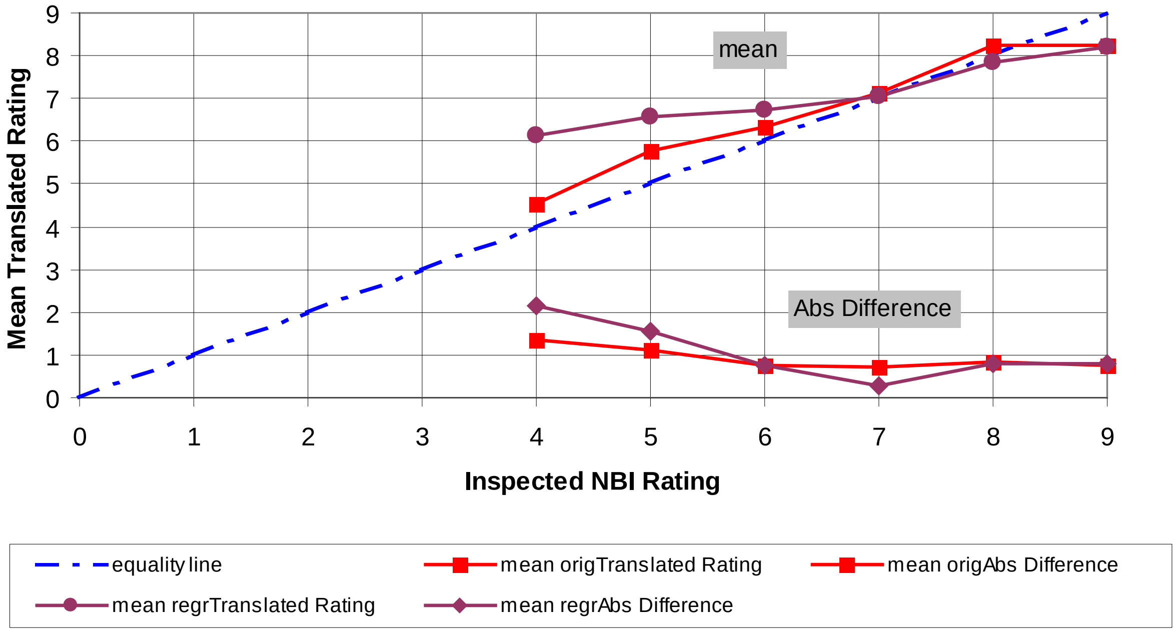


Figure 3.10. Variation in translated ratings for decks inspected in 2007 on state-maintained bridges

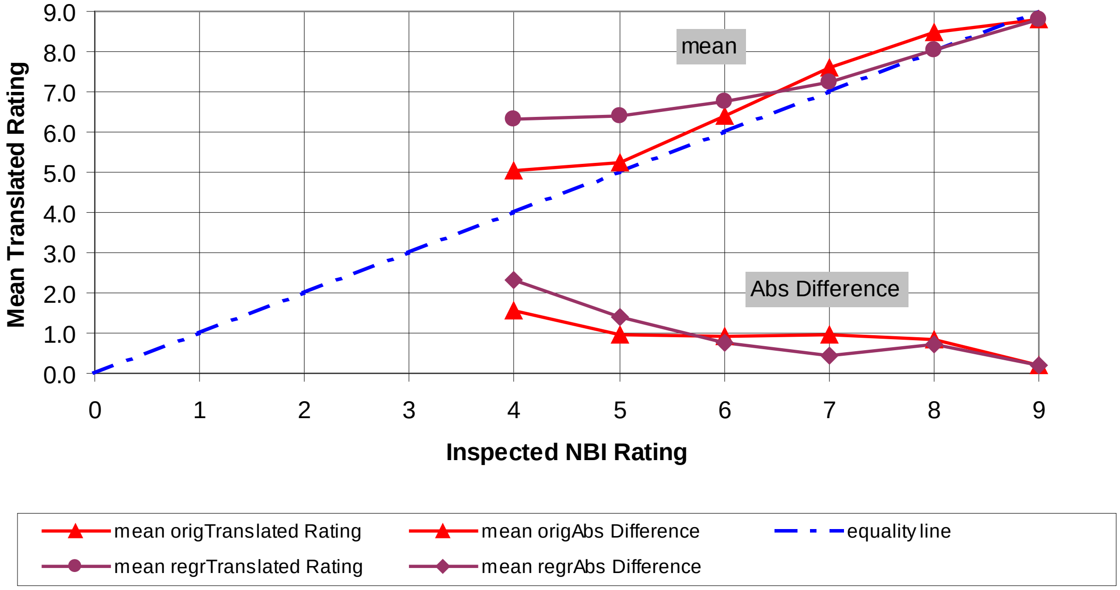


Figure 3.11. Variation in translated ratings for decks inspected in 2008 on state-maintained bridges

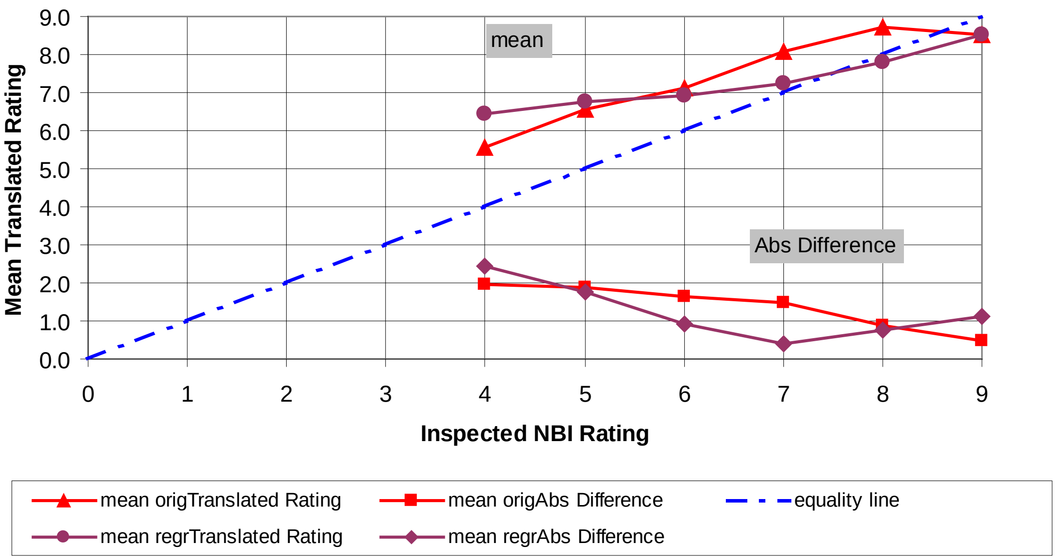


Figure 3.12. Variation in translated ratings for superstructures inspected in 2007 on state-maintained bridges

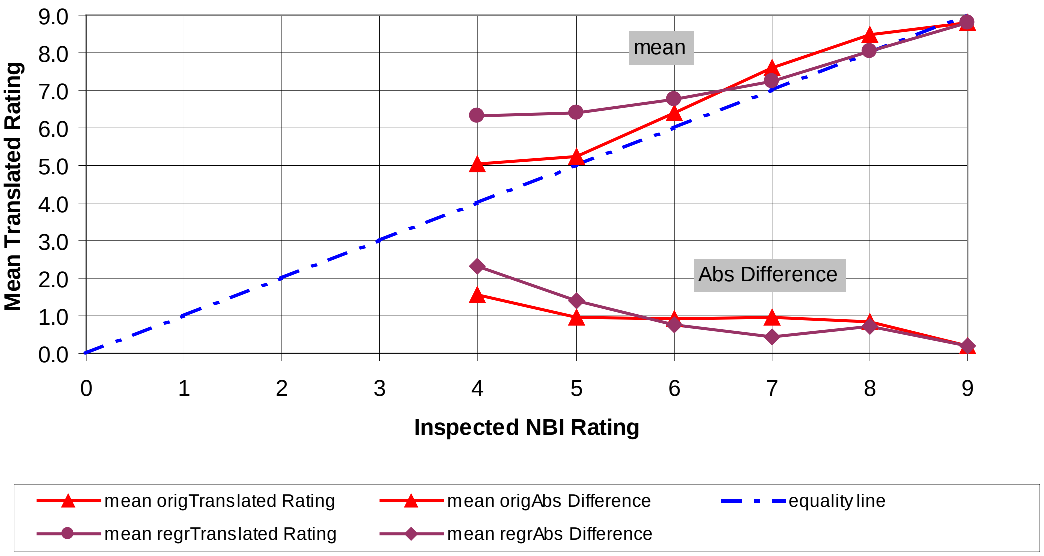


Figure 3.13. Variation in translated ratings for superstructures inspected in 2008 on state-maintained bridges

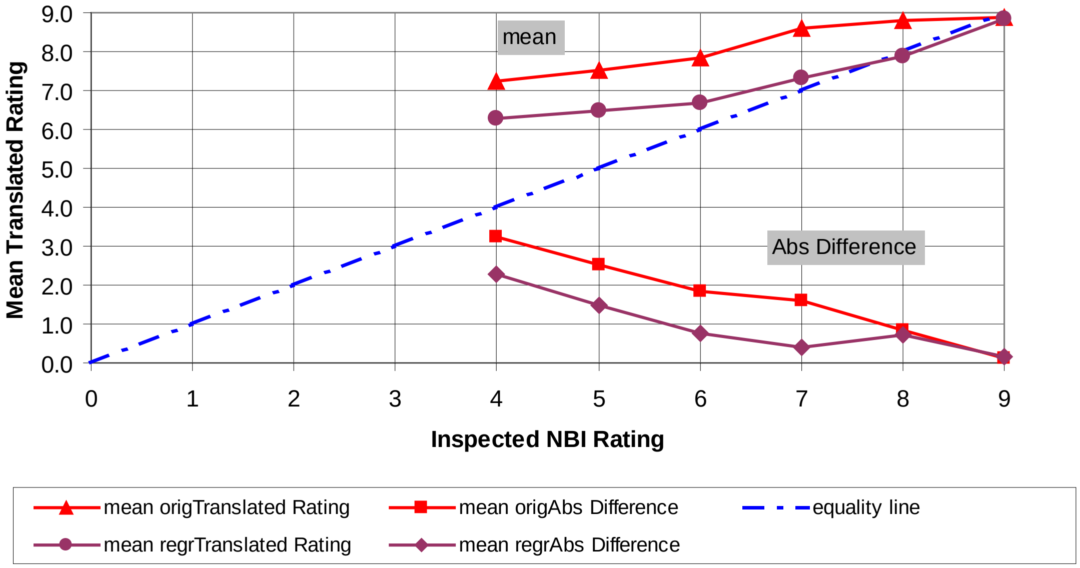


Figure 3.14. Variation in translated ratings for substructures inspected in 2007 on state-maintained bridges

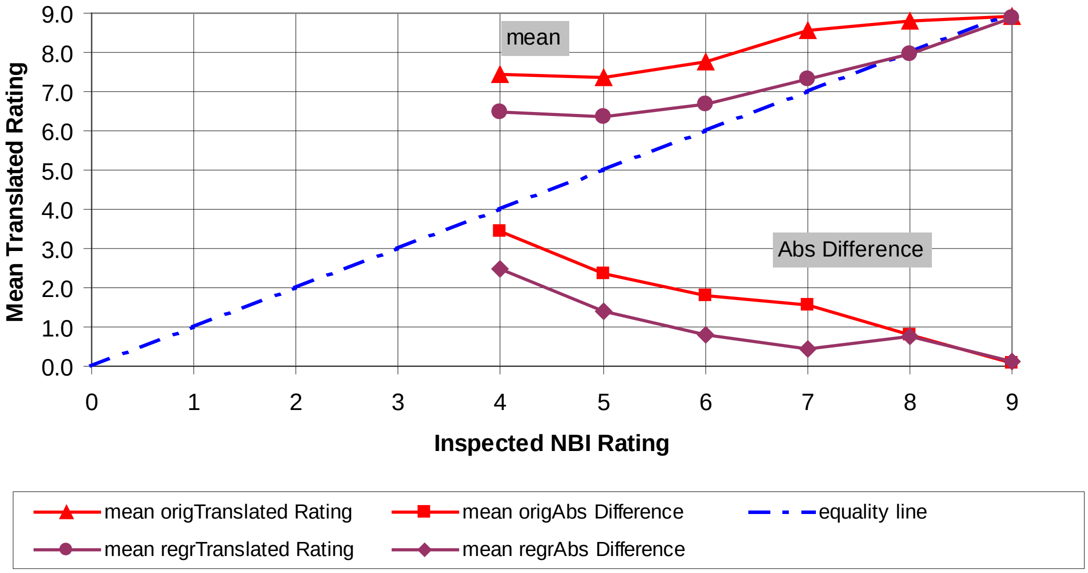


Figure 3.15. Variation in translated ratings for substructures inspected in 2008 on state-maintained bridges.

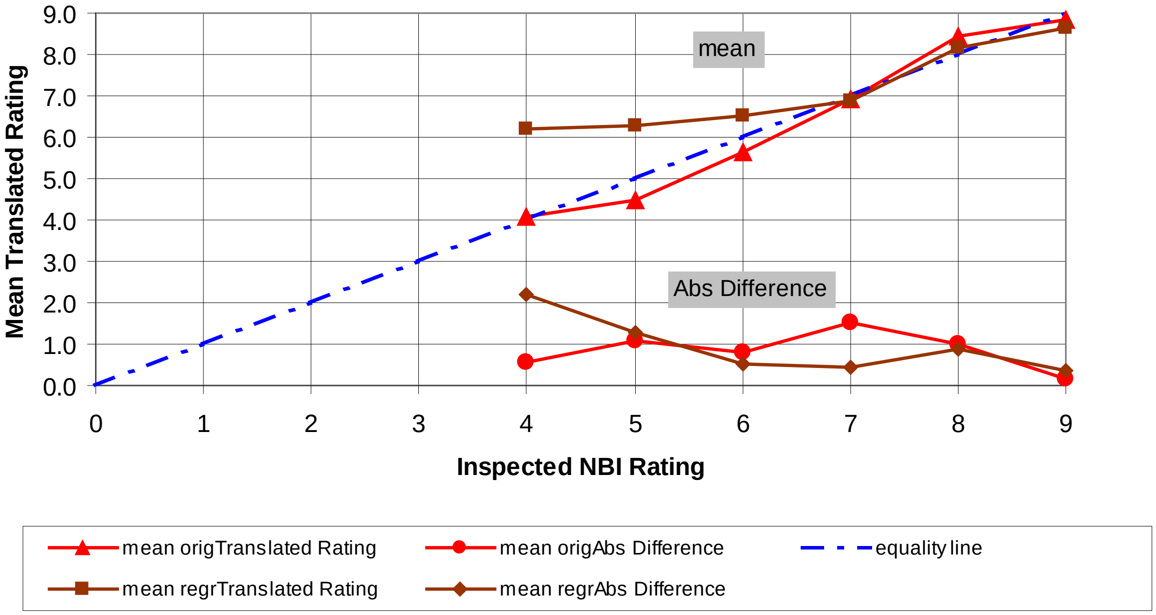


Figure 3.16. Variation in translated ratings for culverts inspected in 2007 on state-maintained bridges

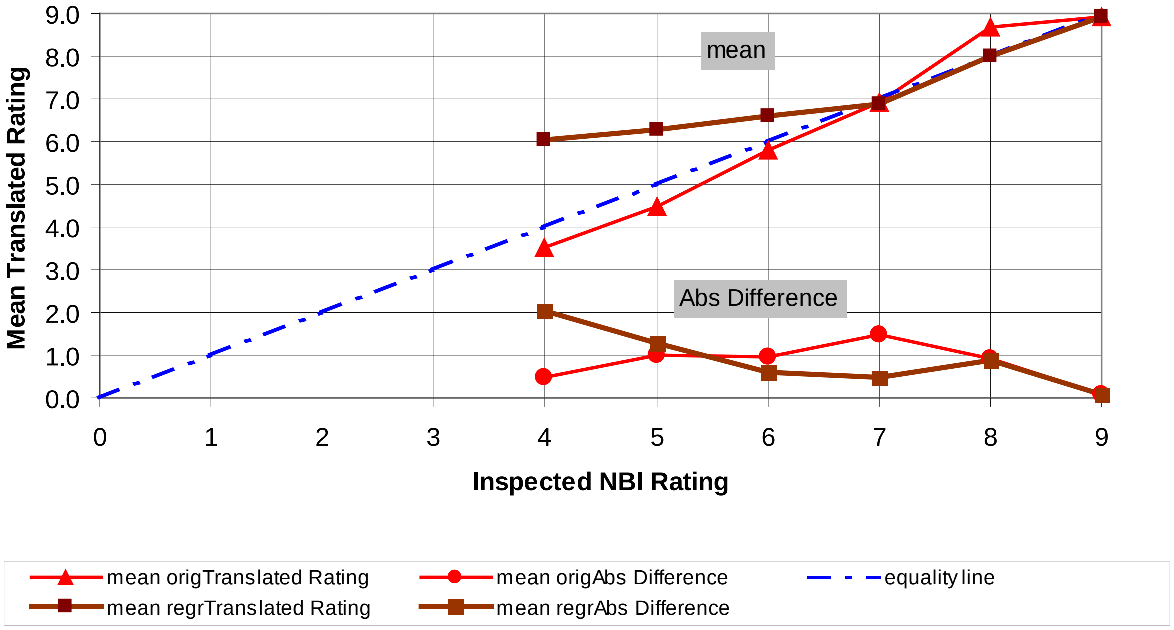


Figure 3.17. Variation in translated ratings for culverts inspected in 2008 on state-maintained bridges

Table 3.27. Summary of rounded original translated ratings for 2008 inspected decks on state-maintained bridges (35.1% exact translations)

% all	#inspNBI	x	y	z	% all	% inspNBI
0.3%	6	4	3	0	0.0%	0.0%
		4	4	0	0.0%	0.0%
		4	5	4	0.2%	57.1%
		4	6	2	0.1%	28.6%
		4	7	0	0.0%	0.0%
		4	8	0	0.0%	0.0%
		4	9	0	0.0%	0.0%
2.1%	38	5	3	3	0.2%	7.9%
		5	4	8	0.4%	21.1%
		5	5	12	0.7%	31.6%
		5	6	10	0.5%	26.3%
		5	7	5	0.3%	13.2%
		5	8	0	0.0%	0.0%
		5	9	0	0.0%	0.0%
8.2%	151	6	3	0	0.0%	0.0%
		6	4	2	0.1%	1.3%
		6	5	35	1.9%	23.2%
		6	6	44	2.4%	29.1%
		6	7	53	2.9%	35.1%
		6	8	7	0.4%	4.6%
		6	9	10	0.5%	6.6%
67.0%	1232	7	3	0	0.0%	0.0%
		7	4	1	0.1%	0.1%
		7	5	2	0.1%	0.2%
		7	6	204	11.1%	16.6%
		7	7	488	26.6%	39.6%
		7	8	104	5.7%	8.4%
		7	9	433	23.6%	35.1%
20.8%	383	8	3	0	0.0%	0.0%
		8	4	0	0.0%	0.0%
		8	5	0	0.0%	0.0%
		8	6	17	0.9%	4.4%
		8	7	37	2.0%	9.7%
		8	8	78	4.2%	20.4%
		8	9	251	13.7%	65.5%
1.5%	27	9	3	0	0.0%	0.0%
		9	4	0	0.0%	0.0%
		9	5	0	0.0%	0.0%
		9	6	0	0.0%	0.0%
		9	7	1	0.1%	3.7%
		9	8	3	0.2%	11.1%
		9	9	23	1.3%	85.2%

Table 3.28. Summary of rounded regression- modified translated ratings for 2008 inspected decks on state-maintained bridges (52.3% exact translations)

% all	#inspNBI	x	y	z	% all	% inspNBI
0.4%	7	4	3	0	0.0%	0.0%
		4	4	0	0.0%	0.0%
		4	5	1	0.1%	14.3%
		4	6	4	0.2%	57.1%
		4	7	2	0.1%	28.6%
		4	8	0	0.0%	0.0%
		4	9	0	0.0%	0.0%
2.1%	38	5	3	0	0.0%	0.0%
		5	4	0	0.0%	0.0%
		5	5	0	0.0%	0.0%
		5	6	25	1.4%	65.8%
		5	7	13	0.7%	34.2%
		5	8	0	0.0%	0.0%
		5	9	0	0.0%	0.0%
8.2%	151	6	3	0	0.0%	0.0%
		6	4	0	0.0%	0.0%
		6	5	1	0.1%	0.7%
		6	6	38	2.1%	25.2%
		6	7	102	5.5%	67.5%
		6	8	10	0.5%	6.6%
		6	9	0	0.0%	0.0%
67.0%	1232	7	3	0	0.0%	0.0%
		7	4	0	0.0%	0.0%
		7	5	1	0.1%	0.1%
		7	6	16	0.9%	1.3%
		7	7	784	42.7%	63.6%
		7	8	338	18.4%	27.4%
		7	9	93	5.1%	7.5%
20.8%	383	8	3	0	0.0%	0.0%
		8	4	0	0.0%	0.0%
		8	5	0	0.0%	0.0%
		8	6	3	0.2%	0.8%
		8	7	111	6.0%	29.0%
		8	8	117	6.4%	30.5%
		8	9	152	8.3%	39.7%
1.5%	27	9	3	0	0.0%	0.0%
		9	4	0	0.0%	0.0%
		9	5	0	0.0%	0.0%
		9	6	0	0.0%	0.0%
		9	7	1	0.1%	3.7%
		9	8	3	0.2%	11.1%
		9	9	23	1.3%	85.2%

Table 3.29. Summary of rounded regression-modified translated ratings for 2008 inspected superstructures on state-maintained bridges (55.1% exact translations)

% all	#inspNBI	x	y	z	% all	% inspNBI
0.4%	8	4	3	0	0.0%	0.0%
		4	4	0	0.0%	0.0%
		4	5	0	0.0%	0.0%
		4	6	3	0.2%	37.5%
		4	7	5	0.3%	62.5%
		4	8	0	0.0%	0.0%
		4	9	0	0.0%	0.0%
2.1%	39	5	3	0	0.0%	0.0%
		5	4	0	0.0%	0.0%
		5	5	0	0.0%	0.0%
		5	6	14	0.8%	35.9%
		5	7	25	1.4%	64.1%
		5	8	0	0.0%	0.0%
		5	9	0	0.0%	0.0%
7.5%	138	6	3	0	0.0%	0.0%
		6	4	1	0.1%	0.7%
		6	5	0	0.0%	0.0%
		6	6	25	1.4%	18.1%
		6	7	111	6.1%	80.4%
		6	8	1	0.1%	0.7%
		6	9	0	0.0%	0.0%
56.9%	1040	7	3	0	0.0%	0.0%
		7	4	1	0.1%	0.1%
		7	5	0	0.0%	0.0%
		7	6	27	1.5%	2.6%
		7	7	940	51.4%	90.4%
		7	8	6	0.3%	0.6%
		7	9	66	3.6%	6.3%
31.0%	566	8	3	0	0.0%	0.0%
		8	4	0	0.0%	0.0%
		8	5	0	0.0%	0.0%
		8	6	2	0.1%	0.4%
		8	7	344	18.8%	60.8%
		8	8	6	0.3%	1.1%
		8	9	214	11.7%	37.8%
2.0%	37	9	3	0	0.0%	0.0%
		9	4	0	0.0%	0.0%
		9	5	0	0.0%	0.0%
		9	6	0	0.0%	0.0%
		9	7	0	0.0%	0.0%
		9	8	0	0.0%	0.0%
		9	9	37	2.0%	100.0%

Table 3.30. Summary of rounded regression-modified translated ratings for 2008 inspected substructures on state-maintained bridges (54.2% exact translations)

% all	#inspNBI	x	y	z	% all	% inspNBI
1.5%	27	4	3	0	0.0%	0.0%
		4	4	1	0.1%	3.7%
		4	5	2	0.1%	7.4%
		4	6	8	0.4%	29.6%
		4	7	15	0.8%	55.6%
		4	8	0	0.0%	0.0%
		4	9	1	0.1%	3.7%
1.6%	29	5	3	0	0.0%	0.0%
		5	4	0	0.0%	0.0%
		5	5	4	0.2%	13.8%
		5	6	15	0.8%	51.7%
		5	7	10	0.5%	34.5%
		5	8	0	0.0%	0.0%
		5	9	0	0.0%	0.0%
7.9%	144	6	3	0	0.0%	0.0%
		6	4	0	0.0%	0.0%
		6	5	9	0.5%	6.3%
		6	6	34	1.9%	23.6%
		6	7	98	5.3%	68.1%
		6	8	3	0.2%	2.1%
		6	9	0	0.0%	0.0%
58.0%	1063	7	3	0	0.0%	0.0%
		7	4	0	0.0%	0.0%
		7	5	10	0.5%	0.9%
		7	6	31	1.7%	2.9%
		7	7	919	50.2%	86.5%
		7	8	34	1.9%	3.2%
		7	9	69	3.8%	6.5%
29.3%	537	8	3	0	0.0%	0.0%
		8	4	0	0.0%	0.0%
		8	5	0	0.0%	0.0%
		8	6	2	0.1%	0.4%
		8	7	318	17.4%	59.2%
		8	8	4	0.2%	0.7%
		8	9	213	11.6%	39.7%
1.7%	32	9	3	0	0.0%	0.0%
		9	4	0	0.0%	0.0%
		9	5	0	0.0%	0.0%
		9	6	0	0.0%	0.0%
		9	7	1	0.1%	3.1%
		9	8	0	0.0%	0.0%
		9	9	31	1.7%	96.9%

Table 3.31. Summary of rounded regression-modified translated ratings for 2008 inspected state-maintained culverts (47.6% exact translations)

% all	#inspNBI	x	y	z	% all	% inspNBI
0.3%	1	4	3	0	0.0%	0.0%
		4	4	0	0.0%	0.0%
		4	5	0	0.0%	0.0%
		4	6	1	0.3%	100.0%
		4	7	0	0.0%	0.0%
		4	8	0	0.0%	0.0%
		4	9	0	0.0%	0.0%
3.2%	10	5	3	0	0.0%	0.0%
		5	4	0	0.0%	0.0%
		5	5	0	0.0%	0.0%
		5	6	9	2.9%	90.0%
		5	7	1	0.3%	10.0%
		5	8	0	0.0%	0.0%
		5	9	0	0.0%	0.0%
19.7%	62	6	3	0	0.0%	0.0%
		6	4	0	0.0%	0.0%
		6	5	0	0.0%	0.0%
		6	6	45	14.3%	72.6%
		6	7	16	5.1%	25.8%
		6	8	0	0.0%	0.0%
		6	9	1	0.3%	1.6%
70.5%	222	7	3	0	0.0%	0.0%
		7	4	0	0.0%	0.0%
		7	5	0	0.0%	0.0%
		7	6	104	33.0%	46.8%
		7	7	104	33.0%	46.8%
		7	8	2	0.6%	0.9%
		7	9	12	3.8%	5.4%
6.0%	19	8	3	0	0.0%	0.0%
		8	4	0	0.0%	0.0%
		8	5	0	0.0%	0.0%
		8	6	1	0.3%	5.3%
		8	7	9	2.9%	47.4%
		8	8	0	0.0%	0.0%
		8	9	9	2.9%	47.4%
0.3%	1	9	3	0	0.0%	0.0%
		9	4	0	0.0%	0.0%
		9	5	0	0.0%	0.0%
		9	6	0	0.0%	0.0%
		9	7	0	0.0%	0.0%
		9	8	0	0.0%	0.0%
		9	9	1	0.3%	100.0%

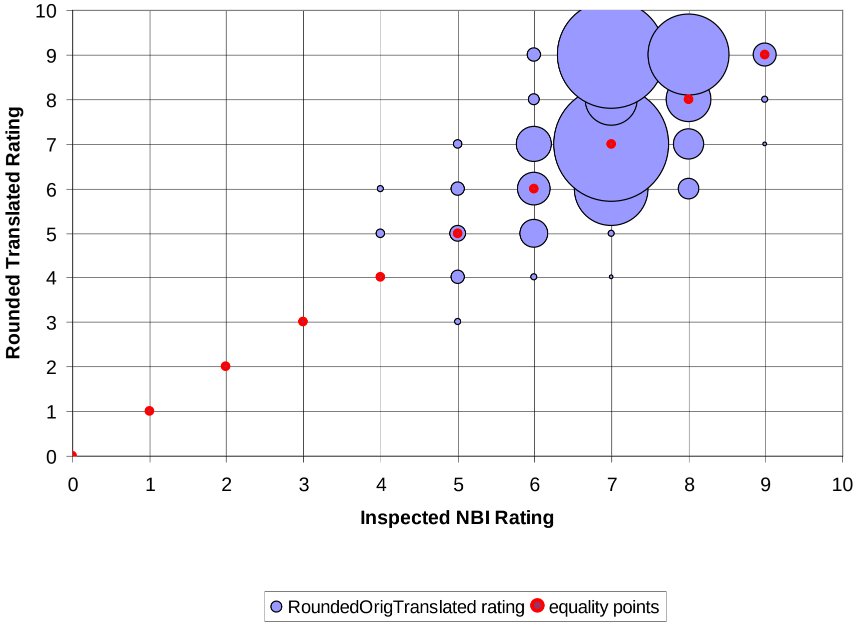


Figure 3.18. Bubble plot for variation in rounded original translated ratings for decks on state-maintained bridges inspected in 2008

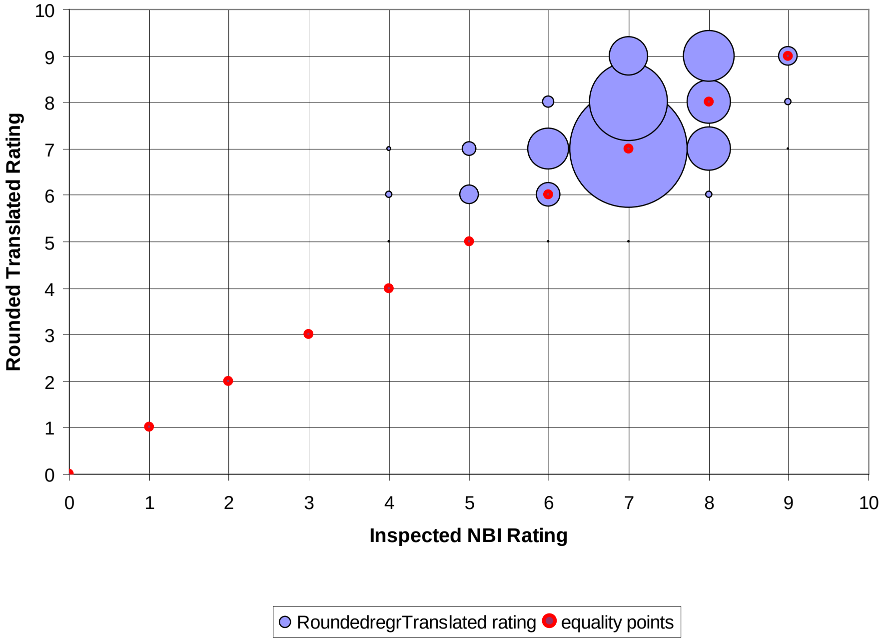


Figure 3.19. Bubble plot for variation in rounded regression-modified translated ratings for decks on state-maintained bridges inspected in 2008.

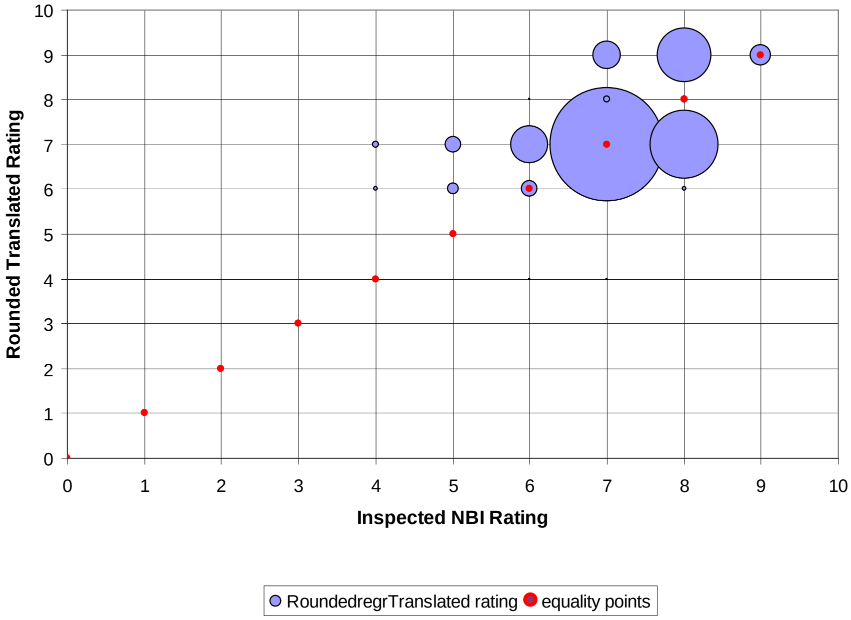


Figure 3.20. Bubble plot for variation in rounded regression-modified translated ratings for superstructures on state-maintained bridges inspected in 2008

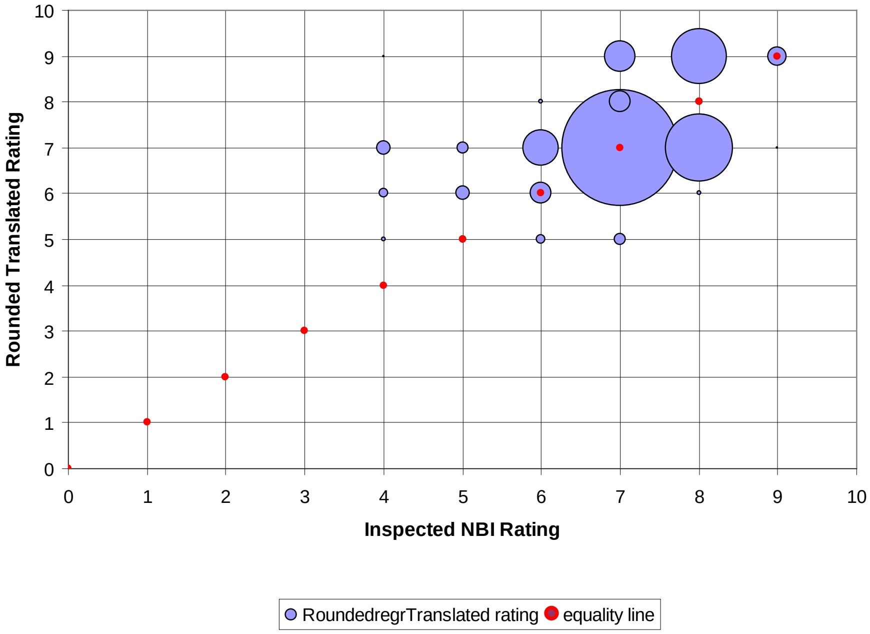


Figure 3.21. Bubble plot for variation in rounded regression-modified translated ratings for substructures on state-maintained bridges inspected in 2008

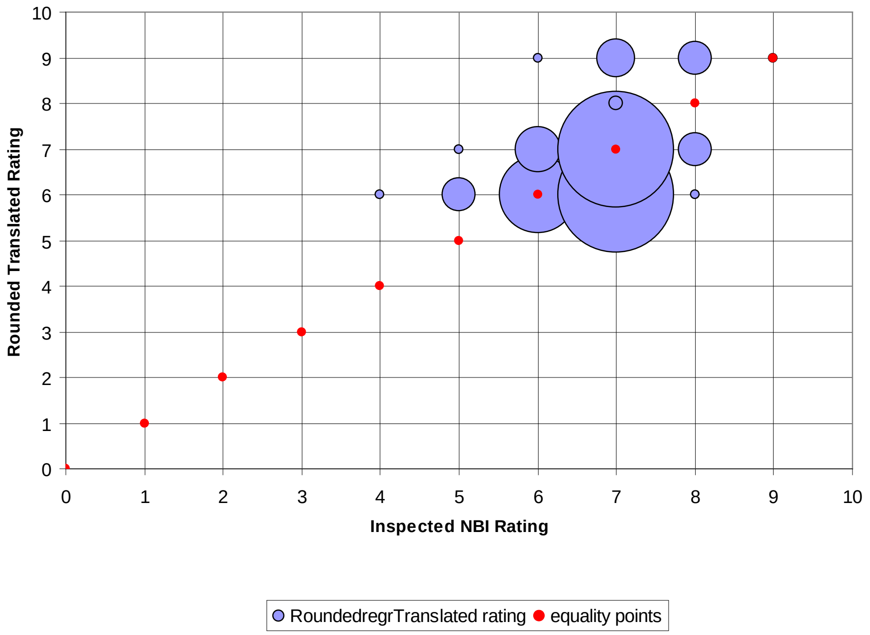


Figure 3.22. Bubble plot for variation in rounded regression-modified translated ratings for state-maintained culverts inspected in 2008

3.5 Refined Translator Model: Microsoft Excel Version

The major requirement of this research task was to develop an NBI Translator that is fully functional in the PLAT model, which was developed on the Microsoft Excel platform (Figure 3.23). This section describes some refinement done to the NBI Translator described above, including case studies to illustrate the methodology and also explain the translation accuracy. One of the refinements done to the translator model was to revise the estimate of relative weights of the elements. Also an optimization algorithm was developed with the goal of estimating the best coefficients for some of the various equations used in the model.

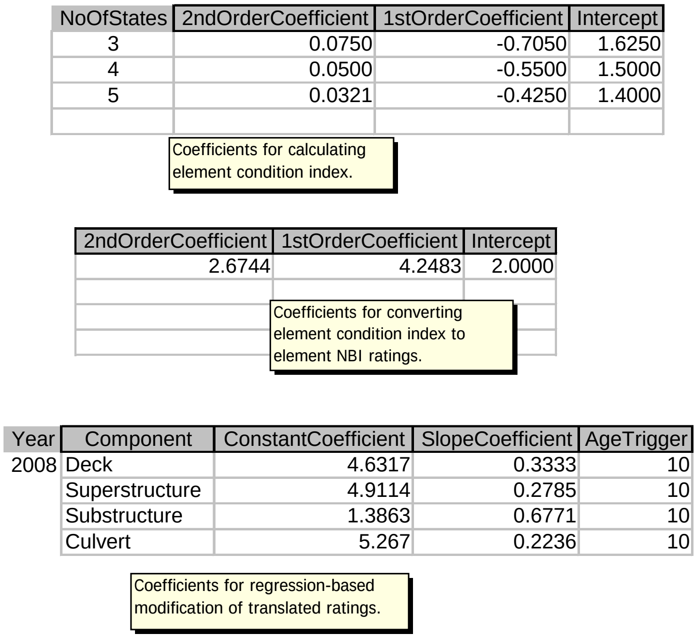
FDOT NBI Translator 2010

This computer spreadsheet program enables the user to translate element-based bridge inspection data (% in deterioration states) to the FHWA NBI (Condition Rating) format. The translation is done for each bridge component (deck, superstructure, substructure, or culvert) separately. Element inspection data from Pontis is stored in the "ElementData2" Worksheet and the elements' assignment to bridge component is indicated, along with suggested initial weights, in the "FactorsBridge" Worksheet. The "InputList" Worksheet has a list of specific bridge(s) (entered by user) and some statistical parameters necessary for optional adjustment or comparison of the translated ratings.

First the element inspection data is read and separated into bridge component data, with the element condition indexes and NBI condition ratings also calculated. Starting with the initial user-assigned relative weights, the elements' quantities are used to estimate the relative weights of importance for the elements on each bridge components. Next , the weights are used to aggregate the NBI condition ratings of the respective elements constituting each bridge component. The smart flags are then used, if indicated in the bridge records, to adjust the translated ratings. Finally, if the field-inspected NBI ratings are available, the translated ratings are compared, and also adjusted based on some statistical parameters. The translated ratings are stored in the "TranslatedRatingDeck" "TranslatedRatingSup" "TranslatedRatingSub" and "TranslatedRatingCulv" Worksheets.

Figure 3.23. Cover screen of Excel-Based refined NBI Translator

The computer spreadsheet program enables the user to translate element-based bridge inspection data (% in deterioration states) to the FHWA's NBI (Condition Rating) format. The translation is done for each bridge component (deck, superstructure, substructure, or culvert) separately. Element inspection data from Pontis is stored in the "ElementData2" Worksheet and the elements' assignment to bridge component is indicated, along with suggested initial weights, in the "FactorsBridge" Worksheet. The "InputList" Worksheet has a list of specific bridge(s) (entered by user) and some statistical parameters necessary for computation of indexes, ratings, and adjustment or comparison of the translated ratings (Figure 3.24). First the element inspection data is read and separated into bridge component data, with the element condition indexes and NBI condition ratings also calculated. Starting with the initial user-assigned relative weights, the elements' quantities are used to estimate the relative weights of importance for the elements on each bridge components. Next, the weights are used to aggregate the NBI condition ratings of the respective elements constituting each bridge component. The smart flags are then used, if indicated in the bridge records, to adjust the translated ratings. Finally, if the field-inspected NBI ratings are available, the translated ratings are compared, and also adjusted based on some statistical parameters. The translated ratings are stored in the "TranslatedRatingDeck" "TranslatedRatingSup" "TranslatedRatingSub" and "TranslatedRatingCulv" Worksheets.



NoOfStates	2ndOrderCoefficient	1stOrderCoefficient	Intercept
3	0.0750	-0.7050	1.6250
4	0.0500	-0.5500	1.5000
5	0.0321	-0.4250	1.4000

Coefficients for calculating element condition index.

2ndOrderCoefficient	1stOrderCoefficient	Intercept
2.6744	4.2483	2.0000

Coefficients for converting element condition index to element NBI ratings.

Year	Component	ConstantCoefficient	SlopeCoefficient	AgeTrigger
2008	Deck	4.6317	0.3333	10
	Superstructure	4.9114	0.2785	10
	Substructure	1.3863	0.6771	10
	Culvert	5.267	0.2236	10

Coefficients for regression-based modification of translated ratings.

Figure 3.24. Default coefficients for NBI Translator (condition index calculation, element NBI rating calculation, and regression-based modification)

3.5.1 Estimating optimal condition coefficients

As shown in equations 3.5 to 3.8 earlier, element condition indexes are calculated from expected states of the element while the NBI condition ratings are also estimated from the condition index. With the user-defined importance factors used in estimating each element’s relative weights, the overall component NBI rating is then calculated using equation 3.9. The task here is to estimate the coefficients of these equations and the element’s importance factors, using an optimization algorithm. The simple optimization problem is set up in the Microsoft Excel Solver Program to minimize (set to zero) the difference between inspected NBI Rating and the calculated NBI rating from the element condition data. The spreadsheet template (shown in Table 3.32) is first developed to calculate the element condition indexes, element NBI ratings, and bridge component ratings using equations 3.5 to 3.9. The inputs (shown in Figure 3.25) to these equations include element importance factors (user-defined) and the coefficients in the respective equations. The Solver is applied (using linear programming) to vary the values of these input variables, until the optimal values are obtained for the objective function, i.e.,

Objective function: $$\min \delta = R^o - R \quad = 0 \qquad (3.20)$$

where,

δ = absolute difference between the inspected condition rating and computed rating (from condition index) of bridge component (deck, superstructure, substructure, or culvert), with $0 \le \delta \le 9$.

R^o = the inspected NBI condition rating of bridge component (deck, superstructure, substructure, or culvert), with $2 \leq R^o \leq 9$.

R = the computed NBI condition rating of bridge component (deck, superstructure, substructure, or culvert), with $2 \leq R \leq 9$.

The sum of values in the last column in Table 3.32 is the objective function variable, i.e., sum of absolute differences. Final condition indexes and translated ratings are also indicated. The initial equation coefficients as well as the final values are shown in Figure 3.25. As shown in Table 3.32 the best optimality situation was not obtained (objective function is not zero) for consideration of 25 and 50 bridges, but the set of absolute differences are acceptable. An interesting observation, though, is that this optimization model forces all element condition indexes and NBI ratings to be about 0.8 and 7 respectively. This is not right, given that the corresponding element condition data imply a higher condition index and NBI ratings. In other words, these optimal coefficients are numerically appealing but are not practically useful.

The best statistical explanation for this result is that most bridge components have NBI rating of 7 despite some of them being in excellent condition according to the element-based condition data. Thus in order to satisfy the NBI rating 7, the equation coefficients will be forced to be optimal at values that will always calculate the NBI rating as 7. This also primarily affects coefficients from equations 3.5 to 3.8 and not the other input variables. It is therefore recommended that user-defined levels of element importance and element relative quantities be used in defining the element relative weights.

Table 3.32. Results from optimization run to estimate superstructure elements' condition coefficients

bridge no	elem key	qty	state1	state2	state3	state4	state5	element name	elem wt. factor	num states	unit	Orig cond Index	Orig Elem NBI Rating	Opt. expected state	Opt. cond Index	Opt. NBI Rating	Elem Rel. Wts	Opt. NBI Comp Rating	Insp NBI Ratin	Abs Diff	
10005	38	332.035	0.00	100.00	0.00	0.00	0.00	Bare Concrete Slab	100	5	SM	0.68	6.11	2.0	0.79	7.00	1.00	7.00	7	0.00	
10008	38	385.269	100.00	0.00	0.00	0.00	0.00	Bare Concrete Slab	100	5	SM	1.01	8.99	1.0	0.82	7.18	1.00	7.18	7	0.18	
10011	109	81.077	99.25	0.00	0.00	0.00	0.00	P/S Conc Open Girder	100	4	M	0.99	8.79	1.0	0.81	7.13	1.00	7.13	7	0.13	
10029	107	116.738	89.56	0.00	10.44	0.00	0.00	Paint Stl Opn Girder	100	5	M	0.93	8.29	1.2	0.78	6.91	0.25	6.99	7	0.01	
10029	109	936.041	99.84	0.00	0.00	0.00	0.00	P/S Conc Open Girder	100	4	M	1.00	8.89	1.0	0.81	7.17	0.25				
10029	113	239.573	100.00	0.00	0.00	0.00	0.00	Paint Stl Stringer	50	5	M	1.01	8.99	1.0	0.82	7.18	0.12				
10029	152	64.922	75.12	0.00	24.88	0.00	0.00	Paint Stl Floor Beam	50	5	M	0.84	7.42	1.5	0.76	6.73	0.13				
10029	311	74.000	79.73	20.27	0.00	0.00	0.00	Moveable Bearing	50	3	EA	0.89	7.86	1.2	0.78	6.91	0.13				
10029	313	66.000	81.82	18.18	0.00	0.00	0.00	Fixed Bearing	50	3	EA	0.90	7.96	1.2	0.79	6.93	0.13				
10035	109	1536.000	99.98	0.00	0.00	0.00	0.00	P/S Conc Open Girder	100	4	M	1.00	8.92	1.0	0.82	7.18	0.67	7.12	7	0.12	
10035	310	252.000	0.00	100.00	0.00	0.00	0.00	Elastomeric Bearing	50	3	EA	0.52	4.90	2.0	0.79	7.00	0.33				
10042	38	865.577	0.00	100.00	0.00	0.00	0.00	Bare Concrete Slab	100	5	SM	0.68	6.11	2.0	0.79	7.00	1.00	7.00	7	0.00	
10045	39	1202.815	0.00	100.00	0.00	0.00	0.00	Unp Conc Slab/AC Ovl	100	5	SM	0.68	6.11	2.0	0.79	7.00	1.00	7.00	7	0.00	
10051	39	212.934	100.00	0.00	0.00	0.00	0.00	Unp Conc Slab/AC Ovl	100	5	SM	1.01	8.99	1.0	0.82	7.18	1.00	7.18	7	0.18	
10052	38	212.190	100.00	0.00	0.00	0.00	0.00	Bare Concrete Slab	100	5	SM	1.01	8.99	1.0	0.82	7.18	1.00	7.18	7	0.18	
10067	109	299.000	100.00	0.00	0.00	0.00	0.00	P/S Conc Open Girder	100	4	M	1.00	8.92	1.0	0.82	7.18	0.67	7.18	7	0.18	
10067	310	36.000	100.00	0.00	0.00	0.00	0.00	Elastomeric Bearing	50	3	EA	1.00	8.87	1.0	0.82	7.18	0.33				
10068	109	300.000	100.00	0.00	0.00	0.00	0.00	P/S Conc Open Girder	100	4	M	1.00	8.92	1.0	0.82	7.18	0.67	7.18	7	0.18	
10068	310	36.000	100.00	0.00	0.00	0.00	0.00	Elastomeric Bearing	50	3	EA	1.00	8.87	1.0	0.82	7.18	0.33				
10090	109	725.000	99.96	0.00	0.04	0.00	0.00	P/S Conc Open Girder	100	4	M	1.00	8.92	1.0	0.82	7.18	0.67	7.18	7	0.18	
10090	310	56.000	100.00	0.00	0.00	0.00	0.00	Elastomeric Bearing	50	3	EA	1.00	8.87	1.0	0.82	7.18	0.33				
10091	109	665.000	100.00	0.00	0.00	0.00	0.00	P/S Conc Open Girder	100	4	M	1.00	8.92	1.0	0.82	7.18	0.67	7.18	8	0.82	
10091	310	52.000	100.00	0.00	0.00	0.00	0.00	Elastomeric Bearing	50	3	EA	1.00	8.87	1.0	0.82	7.18	0.33				
10093	99	1870.970	0.00	100.00	0.00	0.00	0.00	PS Conc Slab	100	5	SM	0.68	6.11	2.0	0.79	7.00	1.00	7.00	7	0.00	
10094	99	484.489	0.00	100.00	0.00	0.00	0.00	PS Conc Slab	100	5	SM	0.68	6.11	2.0	0.79	7.00	1.00	7.00	7	0.00	
10095	99	645.026	0.00	100.00	0.00	0.00	0.00	PS Conc Slab	100	5	SM	0.68	6.11	2.0	0.79	7.00	1.00	7.00	7	0.00	
10098	109	556.260	99.78	0.22	0.00	0.00	0.00	P/S Conc Open Girder	100	4	M	1.00	8.91	1.0	0.82	7.18	0.67	7.18	7	0.18	
10098	310	48.000	100.00	0.00	0.00	0.00	0.00	Elastomeric Bearing	50	3	EA	1.00	8.87	1.0	0.82	7.18	0.33				
10100	109	1141.000	99.84	0.16	0.00	0.00	0.00	P/S Conc Open Girder	100	4	M	1.00	8.92	1.0	0.82	7.18	0.67	7.18	7	0.18	
10100	310	136.000	100.00	0.00	0.00	0.00	0.00	Elastomeric Bearing	50	3	EA	1.00	8.87	1.0	0.82	7.18	0.33				
10101	109	791.870	100.00	0.00	0.00	0.00	0.00	P/S Conc Open Girder	100	4	M	1.00	8.92	1.0	0.82	7.18	0.67	7.18	8	0.82	
10101	310	36.000	100.00	0.00	0.00	0.00	0.00	Elastomeric Bearing	50	3	EA	1.00	8.87	1.0	0.82	7.18	0.33				
10102	109	272.491	100.00	0.00	0.00	0.00	0.00	P/S Conc Open Girder	100	4	M	1.00	8.92	1.0	0.82	7.18	0.67	7.18	8	0.82	
10102	310	24.000	100.00	0.00	0.00	0.00	0.00	Elastomeric Bearing	50	3	EA	1.00	8.87	1.0	0.82	7.18	0.33				
10103	109	272.491	100.00	0.00	0.00	0.00	0.00	P/S Conc Open Girder	100	4	M	1.00	8.92	1.0	0.82	7.18	0.67	7.18	8	0.82	
10103	310	24.000	100.00	0.00	0.00	0.00	0.00	Elastomeric Bearing	50	3	EA	1.00	8.87	1.0	0.82	7.18	0.33				
10104	109	3427.000	99.99	0.00	0.00	0.00	0.00	P/S Conc Open Girder	100	4	M	1.00	8.92	1.0	0.82	7.18	0.67	7.18	7	0.18	
10104	310	276.000	100.00	0.00	0.00	0.00	0.00	Elastomeric Bearing	50	3	EA	1.00	8.87	1.0	0.82	7.18	0.33				
14039	99	305.558	100.00	0.00	0.00	0.00	0.00	PS Conc Slab	100	5	SM	1.01	8.99	1.0	0.82	7.18	1.00	7.18	7	0.18	FINAL
14040	99	294.595	0.00	100.00	0.00	0.00	0.00	PS Conc Slab	100	5	SM	0.68	6.11	2.0	0.79	7.00	1.00	7.00	7	0.00	25 bridges
14041	99	295.617	0.00	100.00	0.00	0.00	0.00	PS Conc Slab	100	5	SM	0.68	6.11	2.0	0.79	7.00	1.00	7.00	7	0.00	5.35

Table 3.32. Results from optimization run to estimate elements' condition coefficients (continued)

bridge no	elem key	qty	state1	state2	state3	state4	state5	element name	elem wt. factor	num states	unit	Orig cond Index	Orig Elem NBI Rating	Opt. expected state	Opt. cond Index	Opt. NBI Rating	Elem Rel. Wts	Opt. NBI Comp Rating	Insp NBI Rating	Abs Diff
14044	99	378.208	0.00	100.00	0.00	0.00	0.00	PS Conc Slab	100	5	SM	0.68	6.11	2.0	0.79	7.00	1.00	7.00	7	0.00
14046	99	296.732	0.00	100.00	0.00	0.00	0.00	PS Conc Slab	100	5	SM	0.68	6.11	2.0	0.79	7.00	1.00	7.00	7	0.00
14047	99	255.000	0.00	100.00	0.00	0.00	0.00	PS Conc Slab	100	5	SM	0.68	6.11	2.0	0.79	7.00	1.00	7.00	7	0.00

	FINAL VALUES	INITIALS VALUES
condition index1	0.170	0.032
condition index2	-0.532	-0.425
condition index3	1.177	1.400
NBIRatingIndex1	2.645	2.674
NBIRatingIndex2	4.222	4.248
NBIRatingIndex3	1.980	2.000
12	100	100
13	100	100
28	100	100
29	100	100
30	100	100
31	100	100
32	100	100
38	100	100
39	100	100
54	100	100
55	100	100
98	100	100
99	100	100
101	100	100
102	100	100
104	100	100
105	100	100
106	100	100
107	100	100
109	100	100
110	100	100
111	100	100
112	50	50
113	50	50
115	50	50
545	100	100
546	100	100
547	100	100
548	100	100
549	100	100
550	100	100
560	100	100
561	100	100
562	100	100
563	100	100
564	100	100
565	100	100
570	100	100
571	100	100
572	100	100
573	100	100
574	100	100
580	100	100
581	100	100
582	100	100
583	100	100
590	100	100
591	100	100
592	100	100

elemkeys

importance factors

Figure 3.25. Results from optimization run for model’s coefficients for superstructures

3.5.2 Estimating refined element criteria weights

In estimating the relative weights of each element comprising a bridge component, a method was adopted as a modification from Hearn et al. (1997), based on elements' quantities and the user-defined importance factors. Using the quantity of each element within each identified unit type of the bridge component, a sum is computed for the total quantity for each unit type. An average of the user-defined importance factors is computed for each unit type. The relative weight of each unit type is then computed using these average importance factors. Within each unit type, the relative weight of each element is computed using the ratio of the element quantity to the total quantity of all elements for that unit type. Finally, the overall relative weight of the element at the bridge component is calculated by multiplying the relative weight within unit type, by the relative weight of that unit type. Mathematically, the process for computing the relative weights within a bridge component can be presented in the following equations.

First the average importance factor, awf_j for any particular unit type j is computed as:

$$awf_j = \frac{1}{m_j} \sum_{j=1}^{m_j} wf_{ij} \tag{3.21}$$

where,

wf_{ij} = importance factor of element i with unit type j
m_j = number of elements with unit type j

Next, the relative weight of each unit type with the particular bridge component, or rwt_j is calculated as

$$rwt_j = \frac{awf_j}{\sum_{j=1}^{n} awf_j} \tag{3.22}$$

where,

n = number of unit types j within the bridge component

The relative weight of each element within the unit type, or rwt_{ij} is basically estimated as

$$rwt_{ij} = \frac{q_{ij}}{\sum_{j=1}^{m_j} q_{ij}} \tag{3.23}$$

where,

q_{ij} = quantity of element i with unit j

The relative weight of each element at the bridge component, or w_i is computed as

$$w_i = rwt_{ij} rwt_j \tag{3.24}$$

Finally, the translated component rating is computed as

$$R = \sum_{1}^{N} r_i w_i \tag{3.25}$$

where,

R = the computed condition rating of bridge component (deck, superstructure, substructure, or culvert), with $2 \le R \le 9$.

r_i = the computed NBI rating of element *i*, with $2 \le r_i \le 9$.
w_i = relative weight for bridge element *i*
N = number of elements in the bridge component (deck, superstructure, substructure, or culvert).

3.5.3 Case studies and review of refined model

For illustration purposes, let us consider the data shown in Table 3.33 for Bridge ID 010029's substructure, where there are three unit types – EA, M, and SM. Based on the user-defined importance factors for each element, the average importance factor for the unit types are 80, 100, and 50 respectively, with the relative weights of 0.348, 0.435, and 0.217. Using equations 3.21 to 25, the relative weights of each element is computed to derive the values shown in Table 3.33. For example, for element no. 204 "P/S Conc Column" the relative weight within the unit, is calculated as the ratio of element quantity (68 EA) to the sum of quantities for Unit EA (139 EA), giving the value of 0.489. The product of 0.89 and the average importance factor for the unit type EA (0.348) yields the relative weight of 0.170, shown in the last column in the table. The sum of the products of relative weights and the computed element NBI ratings, i.e., (0.170*8.80)+(0.005*8.92)+(0.003*8.92)+…+(0.013*7.70)+(0.217*8.82), will result in the overall translated rating of the component, in this case, computed as 8.8.

Table 3.33. Sample calculation of element relative weight at Bridge ID 10029's substructure

ElemKey	Total Qty of Element	Element Name	Element NBIRating	Element Importance Factor	Unit	Sum of Qty in Unit	Average Importance Factor of Unit	Relative Wt. of Unit	Relative Wt. Within Unit	Relative Wt. of Element
204	68.00	P/S Conc Column	8.80	100	EA				0.489	**0.170**
220	2.00	R/C Sub Pile Cap/Ftg	8.92	100	EA				0.014	**0.005**
290	1.00	Channel	8.92	20	EA				0.007	**0.003**
299	68.00	Pile Jacket/Cath Pro	8.92	100	EA	139.000	80	0.348	0.489	**0.170**
210	24.99	R/Conc Pier Wall	7.39	100	M				0.073	**0.032**
215	22.86	R/Conc Abutment	8.92	100	M				0.067	**0.029**
231	18.90	Paint Stl Cap	8.99	100	M				0.055	**0.024**
234	156.06	R/Conc Cap	8.89	100	M				0.458	**0.199**
387	107.90	P/S Fender/Dolphin	8.87	100	M				0.317	**0.138**
475	10.06	R/Conc Walls	7.70	100	M	340.767	100	0.435	0.030	**0.013**
396	453.74	Other Abut Slope Pro	8.82	50	SM	453.738	50	0.217	1.000	**0.217**
						totals:		1.000		1.000

A second run was performed with the refined version of the NBI translator (Excel Version). Among the 1555 superstructures considered, only 23 had smart flags identified on them. As shown in Table 3.34, most of the smart flags are single for the elements, with three elements having two and one having three smart flags. In some cases, the smart flags helped improve on the translation accuracy (for example, Bridge IDs "120001" "120050" and "150050"), while in other cases, they do not (for example, Bridge IDs "064004" "170113" and "364110"). The smart flags modifications were applied in two ways: using the minimum of multiple smart flags indexes, or the average of the indexes. Each of the two indexes is multiplied with the original translated rating to obtain two types of flag-modified ratings. These are shown in the last two columns of Table 3.34.

In the new Excel model run, there were 1558 substructures considered, and only 46 had smart flags identified on them. As shown in Table 3.35, most of the smart flags are single for the elements, with two elements having two smart flags. In most cases, the smart flags have values of 1.0 which does not modify the translated ratings but a few cases help improve on the translation accuracy (for example, Bridge IDs "130054" and "180021"). On the other hand, the smart flags may have been too drastic in reducing the ratings (for example, Bridge IDs "100260" and "150076").

Table 3.34. List of bridge superstructures with smart flags and the translated ratings

bridgeno	No. of Elements	Inspected NBI Rating	Original Translated Rating	No. of Smart Flags	Min. Smart Flag Cond. Index	Avg. Smart Flag Cond. Index	Flag-Adjusted Min. Translated Rating	Flag-Adjusted Avg. Translated Rating
010029	6	7	8.4	1	1.00	1.00	8.4	8.4
064004	1	4	4.5	1	0.60	0.60	2.7	2.7
064017	1	4	4.5	1	1.00	1.00	4.5	4.5
064083	1	7	8.9	1	1.00	1.00	8.9	8.9
100920	5	6	8.8	1	1.00	1.00	8.8	8.8
120001	4	5	6.6	1	0.60	0.60	4.0	4.0
120028	7	5	7.5	1	1.00	1.00	7.5	7.5
120050	6	5	7.5	2	0.60	0.80	4.5	6.0
120064	7	4	6.9	1	1.00	1.00	6.9	6.9
130006	6	5	6.0	1	0.60	0.60	3.6	3.6
130054	6	5	6.5	1	0.60	0.60	3.9	3.9
130057	6	6	7.2	1	1.00	1.00	7.2	7.2
150028	6	6	7.3	2	1.00	1.00	7.3	7.3
150049	7	6	7.8	2	1.00	1.00	7.8	7.8
150050	7	6	7.2	3	0.60	0.87	4.3	6.2
170113	2	7	8.7	1	0.52	0.52	4.5	4.5
180021	4	5	4.3	1	0.52	0.52	2.2	2.2
184006	5	4	5.2	1	1.00	1.00	5.1	5.1
364040	5	7	7.2	1	1.00	1.00	7.2	7.2
364110	7	4	4.4	1	0.60	0.60	2.6	2.6
700017	2	6	8.9	1	1.00	1.00	8.9	8.9
700111	2	7	8.9	1	1.00	1.00	8.8	8.8
700176	2	7	8.9	1	1.00	1.00	8.9	8.9

Table 3.35. List of bridge substructures with smart flags and the translated ratings

bridgeno	No. of Elements	Inspected NBI Rating	Original Translated Rating	No. of Smart Flags	Min. Smart Flag Cond. Index	Avg. Smart Flag Cond. Index	Flag-Adjusted Min. Translated Rating	Flag-Adjusted Avg. Translated Rating
010029	11	7	8.8	1	1.00	1.00	8.8	8.8
010940	2	7	8.1	1	1.00	1.00	8.1	8.1
030077	4	5	7.9	1	1.00	1.00	7.9	7.9
030093	6	6	7.3	2	1.00	1.00	7.3	7.3

A detailed case study is presented in the following paragraphs, where the element condition data are reviewed as well as the computation of the translated ratings. The bridges were selected at random, for cases where the original translation errors were greater than one. The summaries on the bridges evaluated are shown in Tables 3.36 and 3.37. The condition data and translated ratings are shown in Tables 3.38 to 3.45.

Table 3.36. Summary of bridge data on superstructure case studies

	Bridge ID			
	010029	**100500**	**120001**	**700201**
No. of elements	6	5	5	6
Inspected NBI Rating	7	7	4	7
Year Built	1965	1960	1941	1997
Original Translated Rating	8.44	7.77	6.60	8.92
Regression-Modified Rating	7.26	7.08	6.75	7.40
Smart Flags Index	1.00	None	0.60	None
Smart Flags Modified Rating	8.44	N/A	3.96	N/A

Table 3.37. Summary of bridge data on substructure case studies

	Bridge ID			
	010029	**700081**	**180021**	**574100**
No. of elements	11	11	5	6
Inspected NBI Rating	7	5	4	3
Year Built	1965	1971	1951	1984
Original Translated Rating	8.80	7.19	8.64	8.59
Regression-Modified Rating	7.34	6.25	7.24	7.20
Smart Flags Index	None	None	0.30	None
Smart Flags Modified Rating	N/A	N/A	2.59	N/A

Table 3.38. Inspection data and translated ratings for superstructure Bridge ID 010029

ElemKey	Element Name	Total Qty of Element	% of Qty in state1	% of Qty in state2	% of Qty in state3	% of Qty in state4	% of Qty in state5	Condition Index	Element NBIRating	Element Importance Factor	Unit	Sum of Qty in Unit	Average Importance Factor of Unit	Relative Wt. of Unit	Relative Wt. Within Unit	Relative Wt. of Element
107	Paint Stl Opn Girder	116.74	89.56	0.00	10.44	0.00	0.00	0.93	8.29	100	M				0.086	**0.052**
109	P/S Conc Open Girder	936.04	99.84	0.00	0.00	0.00	0.00	1.00	8.89	100	M				0.690	**0.414**
113	Paint Stl Stringer	239.57	100.00	0.00	0.00	0.00	0.00	1.01	8.99	50	M				0.177	**0.106**
152	Paint Stl Floor Beam	64.92	75.12	0.00	24.88	0.00	0.00	0.84	7.42	50	M	1357.27	75	0.600	0.048	**0.029**
311	Moveable Bearing	74.00	79.73	20.27	0.00	0.00	0.00	0.89	7.86	50	EA				0.529	**0.211**
313	Fixed Bearing	66.00	81.82	18.18	0.00	0.00	0.00	0.90	7.96	50	EA	140.00	50	0.400	0.471	**0.189**
												totals:		1.000		1.000

Table 3.39. Inspection data and translated ratings for superstructure Bridge ID 100500

ElemKey	Element Name	Total Qty of Element	% of Qty in state1	% of Qty in state2	% of Qty in state3	% of Qty in state4	% of Qty in state5	Condition Index	Element NBIRating	Element Importance Factor	Unit	Sum of Qty in Unit	Average Importance Factor of Unit	Relative Wt. of Unit	Relative Wt. Within Unit	Relative Wt. of Element
107	Paint Stl Opn Girder	701.04	0.00	99.30	0.00	0.70	0.00	0.67	6.08	100	M				0.330	**0.220**
109	P/S Conc Open Girder	1426.00	99.98	0.00	0.00	0.00	0.00	1.00	8.92	100	M	2127.04	100	0.667	0.670	**0.447**
310	Elastomeric Bearing	144.00	72.22	27.78	0.00	0.00	0.00	0.85	7.51	50	EA				0.818	**0.273**
311	Moveable Bearing	24.00	62.50	37.50	0.00	0.00	0.00	0.80	7.09	50	EA				0.136	**0.045**
313	Fixed Bearing	8.00	0.00	100.00	0.00	0.00	0.00	0.52	4.90	50	EA	176.00	50	0.333	0.045	**0.015**
												totals:		1.000		1.000

Table 3.40. Inspection data and translated ratings for superstructure Bridge ID 120001

ElemKey	Element Name	Total Qty of Element	% of Qty in state1	% of Qty in state2	% of Qty in state3	% of Qty in state4	% of Qty in state5	Condition Index	Element NBIRating	Element Importance Factor	Unit	Sum of Qty in Unit	Average Importance Factor of Unit	Relative Wt. of Unit	Relative Wt. Within Unit	Relative Wt. of Element
107	Paint Stl Opn Girder	205.13	55.42	44.58	0.00	0.00	0.00	0.85	7.57	100	M				0.698	**0.399**
113	Paint Stl Stringer	68.58	90.67	8.89	0.00	0.00	0.00	0.97	8.61	50	M				0.233	**0.133**
152	Paint Stl Floor Beam	20.12	95.46	1.51	0.00	3.03	0.00	0.97	8.63	50	M	293.83	67	0.571	0.068	**0.039**
313	Fixed Bearing	28.00	0.00	100.00	0.00	0.00	0.00	0.52	4.90	50	EA	28.00	50	0.429	1.000	**0.429**
363*	Section Loss SmFlag	1.00	0.00	100.00	0.00	0.00	0.00	0.60	5.51	100	EA					**1.000**
	* Smart Flag -- condition index applied to original translated component NBI rating											totals:		1.000		1.000

Table 3.41. Inspection data and translated ratings for superstructure Bridge ID 700201

ElemKey	Element Name	Total Qty of Element	% of Qty in state1	% of Qty in state2	% of Qty in state3	% of Qty in state4	% of Qty in state5	Condition Index	Element NBIRating	Element Importance Factor	Unit	Sum of Qty in Unit	Average Importance Factor of Unit	Relative Wt. of Unit	Relative Wt. Within Unit	Relative Wt. of Element
107	Paint Stl Opn Girder	99.97	100.00	0.00	0.00	0.00	0.00	1.01	8.99	100	M				0.163	**0.098**
109	P/S Conc Open Girder	190.50	99.60	0.00	0.00	0.00	0.00	0.99	8.85	100	M				0.310	**0.186**
113	Paint Stl Stringer	237.13	100.00	0.00	0.00	0.00	0.00	1.01	8.99	50	M				0.386	**0.232**
152	Paint Stl Floor Beam	86.87	100.00	0.00	0.00	0.00	0.00	1.01	8.99	50	M	614.48	75	0.600	0.141	**0.085**
310	Elastomeric Bearing	20.00	100.00	0.00	0.00	0.00	0.00	1.00	8.87	50	EA				0.833	**0.333**
313	Fixed Bearing	4.00	100.00	0.00	0.00	0.00	0.00	1.00	8.87	50	EA	24.00	50	0.400	0.167	**0.067**
												totals:		1.000		1.000

Table 3.42. Inspection data and translated ratings for substructure Bridge ID 010029

ElemKey	Element Name	Total Qty of Element	% of Qty in state1	% of Qty in state2	% of Qty in state3	% of Qty in state4	% of Qty in state5	Condition Index	Element NBIRating	Element Importance Factor	Unit	Sum of Qty in Unit	Average Importance Factor of Unit	Relative Wt. of Unit	Relative Wt. Within Unit	Relative Wt. of Element
204	P/S Conc Column	68.00	97.06	2.94	0.00	0.00	0.00	0.99	8.80	100	EA				0.489	**0.170**
220	R/C Sub Pile Cap/Ftg	2.00	100.00	0.00	0.00	0.00	0.00	1.00	8.92	100	EA				0.014	**0.005**
290	Channel	1.00	100.00	0.00	0.00	0.00	0.00	1.00	8.92	20	EA				0.007	**0.003**
299	Pile Jacket/Cath Pro	68.00	100.00	0.00	0.00	0.00	0.00	1.00	8.92	100	EA	139.000	80	0.348	0.489	**0.170**
210	R/Conc Pier Wall	24.99	68.29	24.39	7.32	0.00	0.00	0.83	7.39	100	M				0.073	**0.032**
215	R/Conc Abutment	22.86	100.00	0.00	0.00	0.00	0.00	1.00	8.92	100	M				0.067	**0.029**
231	Paint Stl Cap	18.90	100.00	0.00	0.00	0.00	0.00	1.01	8.99	100	M				0.055	**0.024**
234	R/Conc Cap	156.06	99.81	0.00	0.00	0.00	0.00	1.00	8.89	100	M				0.458	**0.199**
387	P/S Fender/Dolphin	107.90	99.72	0.00	0.00	0.00	0.00	0.99	8.87	100	M				0.317	**0.138**
475	R/Conc Walls	10.06	69.70	30.30	0.00	0.00	0.00	0.87	7.70	100	M	340.767	100	0.435	0.030	**0.013**
396	Other Abut Slope Pro	453.74	97.93	1.99	0.00	0.00	0.00	0.99	8.82	50	SM	453.738	50	0.217	1.000	**0.217**
												totals:		1.000		1.000

Table 3.43. Inspection data and translated ratings for substructure Bridge ID 700081

ElemKey	Element Name	Total Qty of Element	% of Qty in state1	% of Qty in state2	% of Qty in state3	% of Qty in state4	% of Qty in state5	Condition Index	Element NBIRating	Element Importance Factor	Unit	Sum of Qty in Unit	Average Importance Factor of Unit	Relative Wt. of Unit	Relative Wt. Within Unit	Relative Wt. of Element
204	P/S Conc Column	160.00	99.38	0.63	0.00	0.00	0.00	1.00	8.90	100	EA				0.773	**0.269**
205	R/Conc Column	24.00	91.67	0.00	8.33	0.00	0.00	0.93	8.23	100	EA				0.116	**0.040**
220	R/C Sub Pile Cap/Ftg	22.00	0.00	100.00	0.00	0.00	0.00	0.60	5.51	100	EA				0.106	**0.037**
290	Channel	1.00	100.00	0.00	0.00	0.00	0.00	1.00	8.92	20	EA	207.00	80	0.348	0.005	**0.002**
210	R/Conc Pier Wall	15.85	0.00	61.54	38.46	0.00	0.00	0.47	4.61	100	M				0.031	**0.014**
215	R/Conc Abutment	22.00	98.61	1.38	0.00	0.00	0.00	0.99	8.86	100	M				0.043	**0.019**
234	R/Conc Cap	150.00	0.00	100.00	0.00	0.00	0.00	0.60	5.51	100	M				0.296	**0.129**
387	P/S Fender/Dolphin	77.72	100.00	0.00	0.00	0.00	0.00	1.00	8.92	100	M				0.153	**0.067**
393	Blkhd Sewl Metal Unc	231.04	0.00	0.00	100.00	0.00	0.00	0.30	3.52	100	M				0.456	**0.198**
475	R/Conc Walls	10.00	100.00	0.00	0.00	0.00	0.00	1.00	8.92	100	M	506.61	100	0.435	0.020	**0.009**
396	Other Abut Slope Pro	2754.00	100.00	0.00	0.00	0.00	0.00	1.00	8.92	50	SM	2754.00	50	0.217	1.000	**0.217**
												totals:		1.000		1.000

Table 3.44. Inspection data and translated ratings for substructure Bridge ID 180021

ElemKey	Element Name	Total Qty of Element	% of Qty in state1	% of Qty in state2	% of Qty in state3	% of Qty in state4	% of Qty in state5	Condition Index	Element NBIRating	Element Importance Factor	Unit	Sum of Qty in Unit	Average Importance Factor of Unit	Relative Wt. of Unit	Relative Wt. Within Unit	Relative Wt. of Element
202	Paint Stl Column	14.00	85.71	14.29	0.00	0.00	0.00	0.96	8.51	100	EA	14.00	100	0.400	1.000	**0.400**
215	R/Conc Abutment	24.00	100.00	0.00	0.00	0.00	0.00	1.00	8.92	100	M				0.462	**0.185**
234	R/Conc Cap	26.00	95.31	0.00	0.00	4.69	0.00	0.94	8.34	100	M				0.500	**0.200**
475	R/Conc Walls	2.00	100.00	0.00	0.00	0.00	0.00	1.00	8.92	100	M	52.00	100	0.400	0.038	**0.015**
396	Other Abut Slope Pro	221.00	100.00	0.00	0.00	0.00	0.00	1.00	8.92	50	SM	221.00	50	0.200	1.000	**0.200**
369*	Sub.Sect Loss SmFlag	1.00	0.00	0.00	100.00	0.00	0.00	0.30	3.52	100	EA					
	* Smart Flag -- condition index applied to original translated component NBI rating											totals:		1.000		1.000

Table 3.45. Inspection data and translated ratings for substructure bridge ID 574100

ElemKey	Element Name	Total Qty of Element	% of Qty in state1	% of Qty in state2	% of Qty in state3	% of Qty in state4	% of Qty in state5	Condition Index	Element NBIRating	Element Importance Factor	Unit	Sum of Qty in Unit	Average Importance Factor of Unit	Relative Wt. of Unit	Relative Wt. Within Unit	Relative Wt. of Element
206	Timber Column	30.00	83.33	13.33	0.00	3.33	0.00	0.90	7.97	100	EA				0.968	**0.276**
290	Channel	1.00	0.00	100.00	0.00	0.00	0.00	0.60	5.51	20	EA	31.00	60	0.286	0.032	**0.009**
216	Timber Abutment	15.24	96.00	4.00	0.00	0.00	0.00	0.98	8.75	100	M				0.253	**0.120**
235	Timber Cap	30.48	97.97	2.03	0.00	0.00	0.00	0.99	8.84	100	M				0.505	**0.241**
476	Timber Walls	14.63	100.00	0.00	0.00	0.00	0.00	1.00	8.92	100	M	60.35	100	0.476	0.242	**0.115**
395	Timber Abut Slope Pr	14.03	100.00	0.00	0.00	0.00	0.00	1.00	8.92	50	SM	14.03	50	0.238	1.000	**0.238**
												totals:		1.000		1.000

For Bridge ID "010029" superstructure (Table 3.38), the primary elements (girders) are in excellent or very good physical conditions, while the secondary elements, stringers and floor beams, are in excellent and good conditions respectively. The supporting elements (bearings) are in close to very good condition. The original translated rating of this substructure component is 8.8 while the inspected NBI rating is 7. Most likely, the bridge inspector is strongly influenced by the floor beam, which is the only element with its condition at about the NBI rating of 7. The overall relative weight (0.029) of the floor beam is small because of its relatively small quantity of about 65 M, thus it does not strongly influence the translated rating of the substructure. There is an indicated smart flag, but with an excellent condition index, resulting in no modification of the translate rating. Using the calibration by the regression model, the translated rating can be modified to 7.34, which is closer to the actual inspected rating.

Looking at Bridge ID "100500" superstructure (Table 3.39), while one of the primary elements, element no. 109, "P/S Conc Open Girder" is in excellent condition, the other girder (element no. 107, "Paint Stl Opn Girder") is in poor condition. The quantities of these elements are about 1430 M and 700 M respectively, which is reflected in the overall relative weights of 0.447 and 0.220. The supporting elements (bearings) are in good condition except for one in very poor condition. The original translated rating of the substructure is 7.77 while the inspected NBI rating is 7. It appears that the "Paint Stl Opn Girder") element (approximately NBI rating 6) may have had the most influence on the bridge inspector but given its smaller quantity relative to the "P/S Conc Open Girder" element (approximately NBI rating 9), the field-assigned rating of 7 may be justified. The calibrated translated rating is almost exactly 7, the inspected NBI rating.

Considering Bridge ID "120001" superstructure (Table 3.40), the primary element (girder) is in between good and very good condition (about NBI rating 7.5) while the secondary elements (stringer and floor beams) are in between very good and excellent conditions (about NBI rating 8.6). The bearings in poor condition (about NBI rating 5), are supporting elements, but have a significant relative weight of 0.447, and strongly influence the original translated rating of 6.6 for this substructure. The inspected NBI rating is 4. The presence of a smart flag (element no. 363, "Section Loss SmFlag") with condition index 0.6 (0 is worst and 1 is best) is applied by direct multiplication, to modify the translated ratings from 6.6 to 3.96, almost the same value as the inspected NBI rating. The calibrated translated rating in this case is 6.75. For Bridge ID "700201" superstructure (Table 3.41), all elements appear to be at or in close to excellent conditions but the inspected NBI rating of the component is 7. The original and calibrated translated ratings are about 8.9 and 7.4 respectively. In this case the difference between the element inspection data and the inspected NBI rating cannot be explained but the calibration brings the translated ratings closer to the field-assigned value.

Looking at Bridge ID "010029" substructure (Table 3.42), all elements appear to be at or in close to excellent conditions, except for element nos. 210 "R/Conc Pier Wall" and 475 "R/Conc Walls" which are in between good and very good conditions (about NBI rating 7.4 and 7.7 respectively). The original translated rating of the substructure is 8.8 while the inspected NBI rating is 7. It appears that the wall elements may have influenced the bridge inspector's rating. The calibrated translated rating is 7.34, which is closer to the inspected NBI rating. For Bridge ID "700081" substructure (Table 3.43), seven of the eleven elements are at or in close to excellent conditions but element nos. 210 "R/Conc Pier Wall " and 393 "Blkhd Sewl Metal Unc" are in poor conditions, with NBI ratings 4.6 and 3.5 respectively. Also, element nos. 220 "R/C Sub Pile Cap/Ftg" and 234 "R/Conc Cap " are in fair conditions, with NBI rating 5.5. The original translated rating is 7.19 while the inspected NBI rating of the component is 5. Element nos. 210 and 220 may have strongly influenced the bridge inspector but their relative quantities are small, thus not as influential in the translated rating. The calibrated translated rating is 6.25.

Considering Bridge ID "180021" substructure (Table 3.44), all elements appear to be at or in close to excellent conditions but the inspected NBI rating of the component is 4. The original and calibrated translated ratings are about 8.6 and 7.2 respectively. The presence of a smart flag (element no. 3693, "Sub.Sect Loss SmFlag") with condition index 0.3 (0 is worst and 1 is best) is applied by direct multiplication, to modify the translated ratings from 8.6 to 2.59, which is very low but closer to the inspected NBI rating. Bridge ID "574100" substructure (Table 3.45), made of timber material, has all its elements appearing to be at or in close to excellent conditions, except for the channel which is in fair condition (NBI rating of 5.51). But the inspected NBI rating of the component is 3. The original and calibrated translated ratings are about 8.6 and 7.2 respectively. Here it can be argued that the condition of the channel may have influenced the bridge inspector in the field, though probably not to the extent of assigning NBI rating 3 for the entire substructure.

Finally the results from the refined Translator model are presented in the following sections and reviewed in terms of the accuracy of the translation. The summaries are shown in Tables 3.46 to 3.49 while the graphs are shown in Figures 3.26 to 3.33. Generally better accuracy of translation was observed for bridge components at NBI rating 6 or higher. For decks, the average of the original translated ratings appear to strongly correlate to all the inspected NBI ratings, while the average error of translation was mostly under one rating (Figures 3.26 and 3.27). With calibration (regression modification), there was a slight improvement in translation accuracy in average translated ratings at NBI ratings greater than 6 for the decks. Looking at translated ratings at individual bridge decks, calibration significantly improved the accuracy of translation, with almost 90% of the bridges having errors less than or equal to one. For other components, the original translated ratings were strongly correlated to the inspected NBI ratings greater than or equal to 6 but not at lower ratings. But these poor condition bridges constitute only a very small portion of the inventory (about 2 to 6%). The effect of calibration of the translated ratings on the bridge superstructures, substructures, and culverts are similar to those of the decks, as shown in Figures 3.28 to 3.33.

Table 3.46. Summary of mean refined translated ratings for bridge decks (2008)

Insp NBI Rating	Original Translation	Calibrated Translation	Error Original Translation	Error Calibrated Translation	Count	% of Bridges
2	2.5	5.4	0.5	3.4	1	0.1%
3	3.4	5.8	0.4	2.8	1	0.1%
4	4.2	6.0	0.8	2.0	3	0.2%
5	4.9	6.3	1.1	1.3	56	3.6%
6	5.9	6.6	0.7	0.6	220	14.1%
7	7.3	7.2	1.1	0.5	1014	65.2%
8	8.4	8.1	1.0	0.9	244	15.7%
9	8.6	8.5	0.4	0.5	17	1.1%
				totals:	1556	100.0%

Table 3.47. Summary of mean refined translated ratings for bridge superstructures (2008)

Insp NBI Rating	Original Translated	Regression Translated	Error Original Translated	Error Regression Translated	Count	% of Bridges
3	6.7	6.8	3.7	3.8	6	0.4%
4	5.6	6.5	1.9	2.5	18	1.2%
5	6.3	6.7	1.9	1.7	65	4.2%
6	6.8	6.8	1.4	0.8	180	11.6%
7	8.0	7.2	1.5	0.5	895	57.6%
8	8.8	8.1	0.9	0.8	369	23.7%
9	8.9	8.9	0.1	0.1	22	1.4%
				totals:	1555	100.0%

Table 3.48. Summary of mean refined translated ratings for bridge substructures (2008)

Insp NBI Rating	Original Translated	Regression Translated	Error Original Translated	Error Regression Translated	Count	% of Bridges
2	6.5	5.9	4.5	3.9	3	0.2%
3	6.9	6.0	3.7	3.0	26	1.7%
4	7.7	6.6	3.6	2.6	38	2.4%
5	7.3	6.4	2.4	1.4	79	5.1%
6	7.7	6.6	1.7	0.8	233	15.0%
7	8.4	7.3	1.5	0.5	835	53.6%
8	8.8	8.1	0.8	0.8	321	20.6%
9	8.9	8.9	0.1	0.1	23	1.5%
				totals:	1558	100.0%

Table 3.49. Summary of mean refined translated ratings for culverts (2008)

Insp NBI Rating	Original Translation	Calibrated Translation	Error Original Translation	Error Calibrated Translation	Count	% of Bridges
2	2.5	5.8	0.5	3.8	1	0.2%
3	2.9	5.9	0.1	2.9	1	0.2%
4	4.1	6.2	0.7	2.2	5	1.2%
5	5.0	6.4	1.0	1.4	27	6.3%
6	5.8	6.6	0.9	0.6	94	21.9%
7	7.1	7.0	1.5	0.5	270	62.8%
8	8.8	8.3	0.9	0.9	31	7.2%
9	8.9	8.9	0.1	0.1	1	0.2%
				totals:	430	100.0%

Figure 3.26. Variation in mean refined translated ratings for bridge decks (2008 inventory)

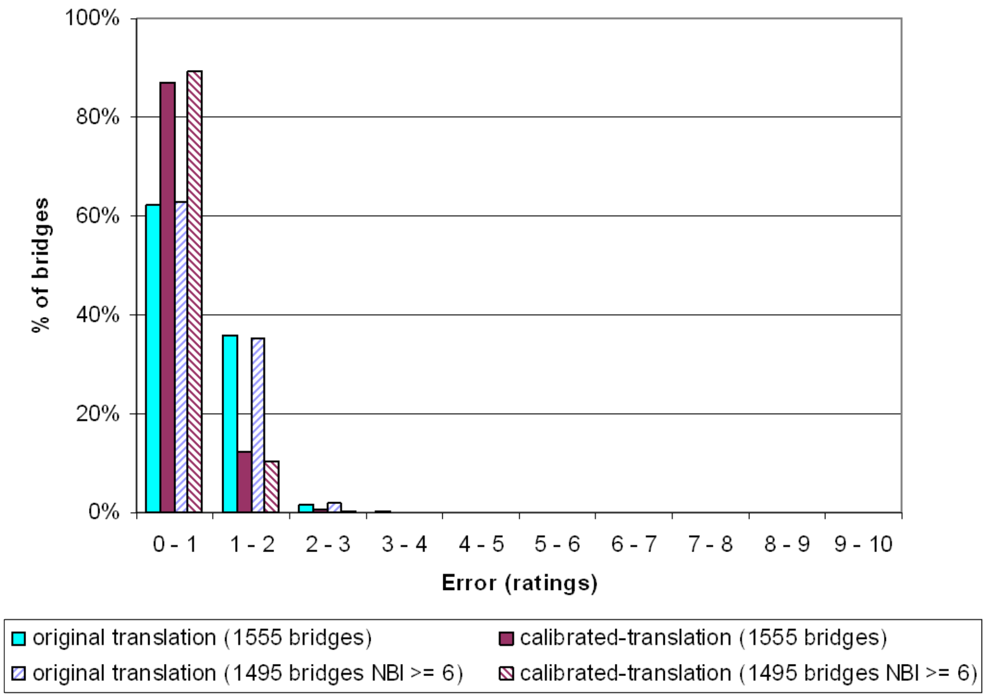


Figure 3.27. Variation in refined translation errors in bridge decks (2008 inventory)

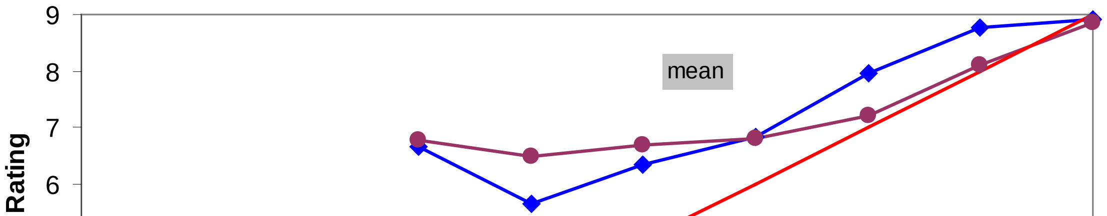


Figure 3.28. Variation in mean refined translated ratings for bridge superstructures (2008 inventory)

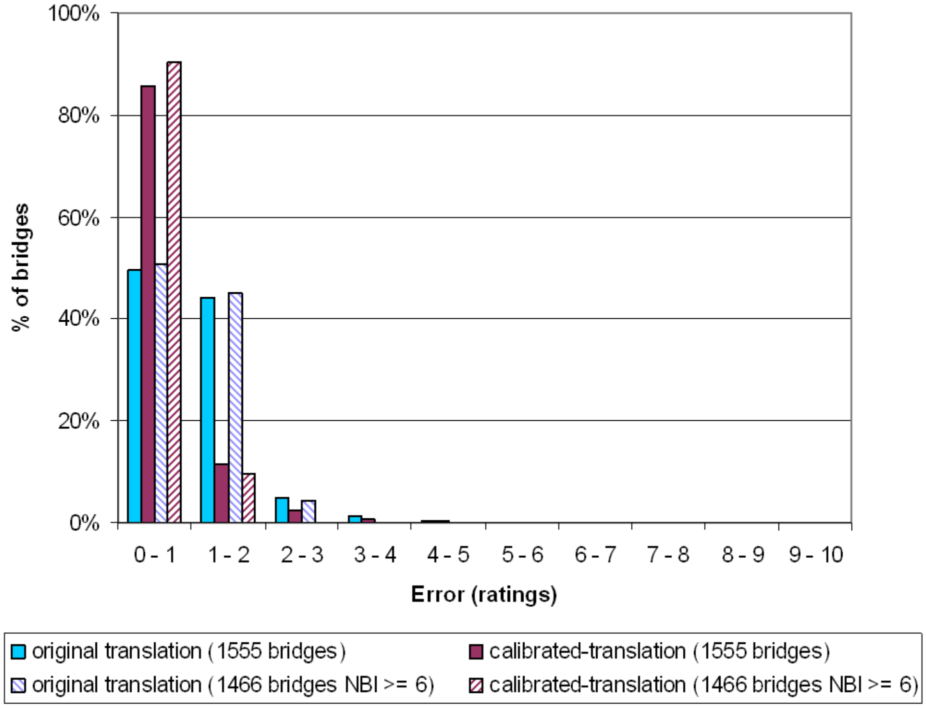


Figure 3.29. Variation in refined translation errors in bridge superstructures (2008 inventory)

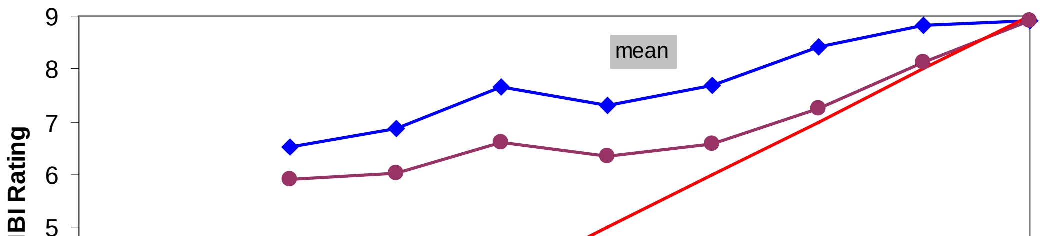


Figure 3.30. Variation in mean refined translated ratings for bridge substructures (2008 inventory)

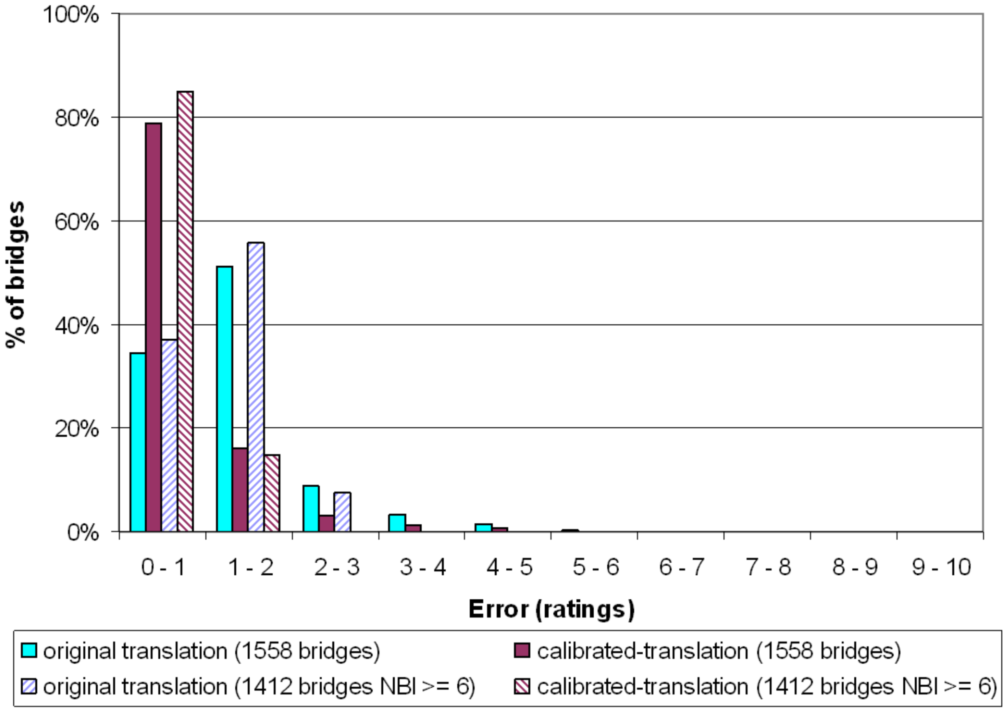


Figure 3.31. Variation in refined translation errors in bridge substructures (2008 inventory)

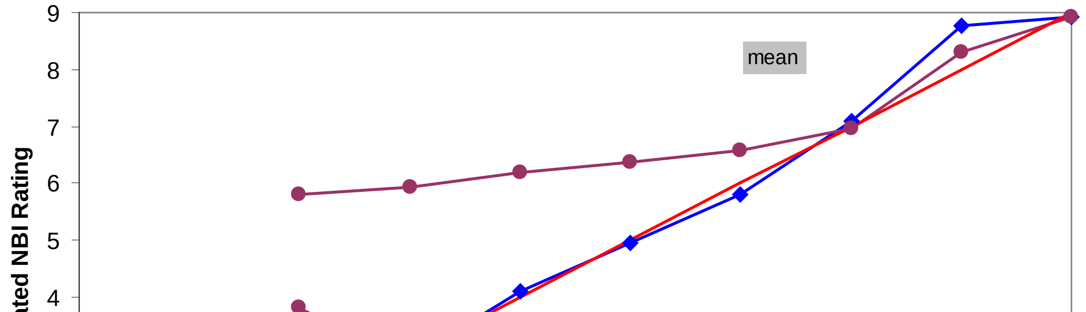
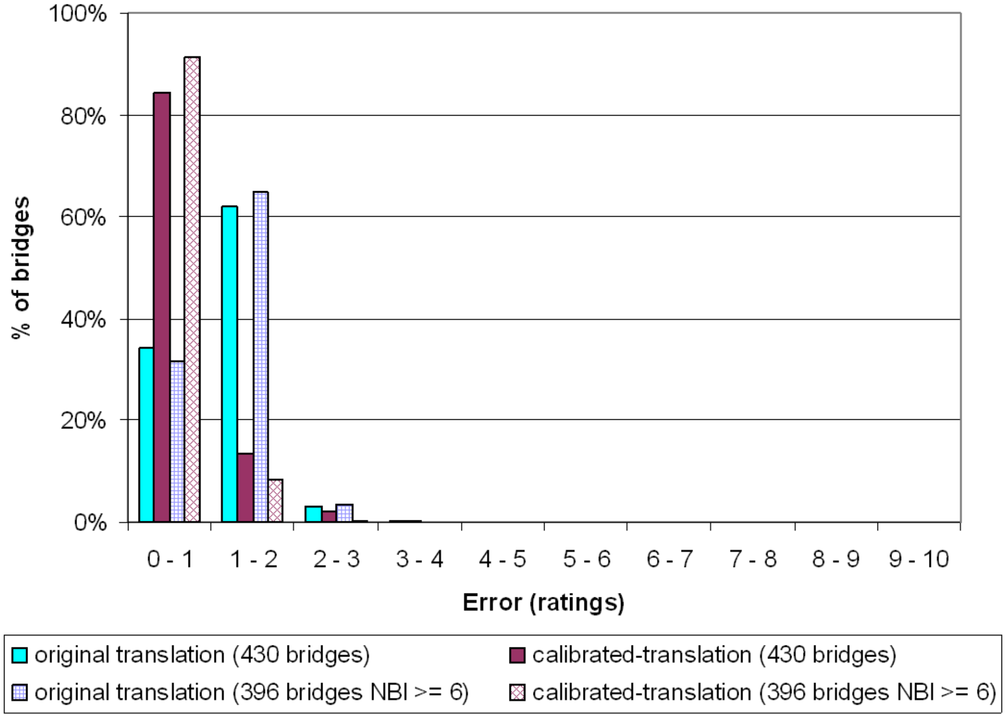


Figure 3.32. Variation in mean refined translated ratings for culverts (2008 inventory)



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3.6. Deterioration Models

One of the uses of bridge condition data is for the development of deterioration models of the bridge major components and its elements. These deterioration models are typically used for predicting the future conditions of the bridge in order to make long-term decisions regarding bridge maintenance, rehabilitation and replacement. The Translator Program was utilized to study the deterioration model formulation by considering the element inspection data, and predicting based on the assumed Markov Chain models in Pontis, the expected condition of bridge elements and then translating the condition indexes to the bridge component's NBI condition ratings.

Following the Markov Chain definition in modeling the bridge deterioration as a stochastic process, the condition of a bridge element currently in a deteriorated state *i*, can be modeled as a random variable which could be in a state *j* with an established one-step transition probability matrix, *P* expressed as follows

$$P = \begin{pmatrix} p_{11} & p_{12} & p_{13} & p_{14} & p_{15} \\ p_{21} & p_{22} & p_{23} & p_{24} & p_{25} \\ p_{31} & p_{32} & p_{33} & p_{34} & p_{35} \\ p_{41} & p_{42} & p_{43} & p_{44} & p_{45} \\ p_{51} & p_{52} & p_{53} & p_{54} & p_{55} \end{pmatrix} \tag{3.26}$$

where,

p_{ij} = Probability of the bridge element in state *i* going to another state *j* in one period.

To illustrate the application of the Translation program, a bridge was selected at random from the bridge inventory (Bridge ID 080056), and deterioration curves were developed for a 70-year service life. First, using the equations explained earlier in this report, the condition indexes of the bridge element, were estimated. As shown in Table 3.50, the bridge deck consists of three elements element nos 12 (Concrete Deck – Bare), 301 (Pourable Seal Joint), and 331 (Reinforced Conc Bridge Railing). The transition probability matrices of the element were retrieved from the Pontis ACTMODLS table and listed as shown in Tables 3.51 to 3.53.

Table 3.50. Sample Bridge 080056's data for deterioration model

elemkey	ecatkey	ecatname	BridgeComponent	ElementShortName	ElementWeightFactor	STATECNT
12	6	Decks/Slabs	Deck	Concrete Deck - Bare	100	5
301	3	Joints	Deck	Pourable Joint Seal	20	3
331	9	Railing	Deck	Reinforced Conc Bridge Railing	20	4

Table 3.51. Transition probability matrix for Element No. 12

	state 1	state 2	state 3	state 4	state 5	failed state
state 1	0.972	0.029	0.000	0.000	0.000	0.000
state 2	0.000	0.962	0.038	0.000	0.000	0.000
state 3	0.000	0.000	0.947	0.054	0.000	0.000
state 4	0.000	0.000	0.000	0.886	0.115	0.000
state 5	0.000	0.000	0.000	0.000	0.750	0.250
failed state	0.000	0.000	0.000	0.000	0.000	1.000

Table 3.52. Transition probability matrix for Element No. 301

	state 1	state 2	state 3	failed state
state 1	0.886	0.115	0.000	0.000
state 2	0.000	0.825	0.175	0.000
state 3	0.000	0.000	0.680	0.320
failed state	0.000	0.000	0.000	1.000

Table 3.53. Transition probability matrix for Element No. 331

	state 1	state 2	state 3	state 4	failed state
state 1	0.976	0.024	0.000	0.000	0.000
state 2	0.000	0.972	0.029	0.000	0.000
state 3	0.000	0.000	0.962	0.038	0.000
state 4	0.000	0.000	0.000	0.943	0.058
failed state	0.000	0.000	0.000	0.000	1.000

Based on the Markov chain concept, the transition probability for *n* periods is simply multiplying *P* by itself *n* times. Therefore, given a current condition probability vector, *COND(0)*, the future condition probability vector after *n* periods, *COND(n)*, of a bridge element is estimated as

$$COND(n) = COND(0) * P^n \tag{3.27}$$

Using these computations, and assuming a new bridge in excellent condition (condition index 1), the deterioration curves based on element condition index are shown in Figure 3.34. The overall bridge NBI condition rating was also computed as the translated rating for each period within the 70-year period and plotted in Figure 3.35.

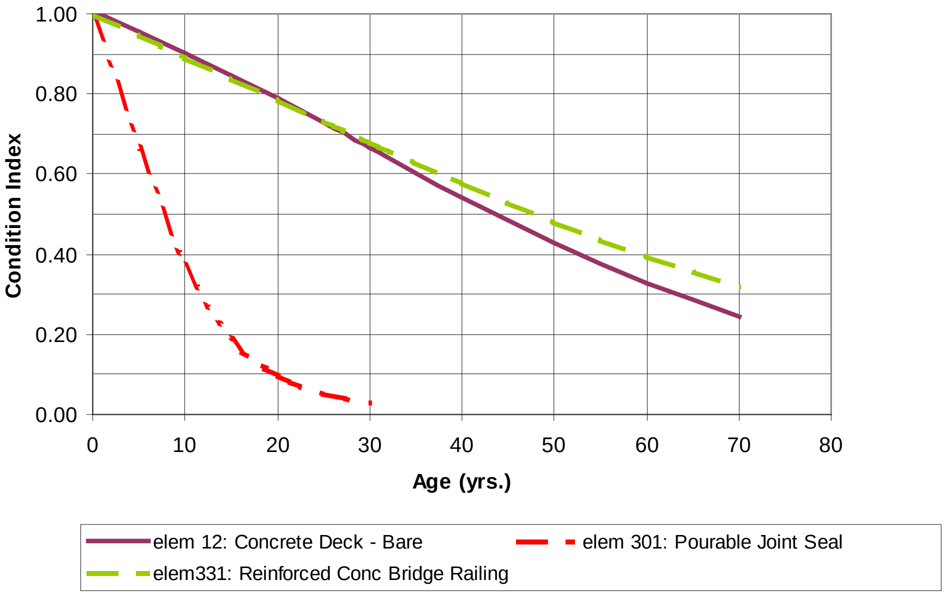


Figure 3.34. Bridge 080056's deck elements' deterioration curves based on condition indexes

Figure 3.35. Bridge 080056's deck deterioration curve based on translated NBI condition ratings

3.7. Conclusions

An improved version for the NBI Translator has been developed and implemented using two years of inspection from the Florida bridge inventory. Bridge substructures tend to have more elements and more complexity (different types of elements) than other components such as deck and superstructures. Please note that channels are included as substructure element but in NBI ratings they are actually separate, with their own ratings. It is assumed here that channels may influence the bridge inspector's rating of the substructure in general. But the relative weight of channels are typically negligible and may be entered as zero in the user table, to totally ignore channel as a substructure.

Extensive research effort was expended in estimating the relative weights of the elements, including use of statistical multiple regression and optimization. Attempts were also made to use optimization algorithms in estimating the coefficients used in the computation of element condition indexes and element NBI ratings. It was concluded that element relative weights are best done using user-defined importance factors and consideration of the element quantities as well as the unit of measure. Optimal coefficients were obtained for estimating element condition indexes and converting these indexes to NBI ratings. But NBI rating 7 was observed as the predominant NBI rating even for excellent condition bridge components and their elements; this produced coefficients that force most of the translated ratings to NBI rating 7. This problem is similar to that of the existing FHWA's NBI Translator, thus the optimal coefficients will not be used. Calibration of the original translated ratings was then done using factors obtained from statistical regression of the data on inspected ratings and translated ratings. During the development of the Translator program, reviews of the initial translated ratings involving case studies at specific bridges were done and the algorithms adjusted as necessary to improve the accuracy of the translated ratings. Extensive case studies were also done on the final Excel version of the NBI Translator, reviewing the translation process at randomly selected bridges. The deterioration models of bridge components and elements were also formulated based on the translated ratings. Overall, the accuracy of the translated ratings, when compared to actual NBI inspected ratings, is significantly better than the FHWA's NBI Translator, and also improved over the previous model of the NBI Translator developed for Florida.

The translation accuracy was generally very good for bridges in NBI ratings 6 or higher, and relatively poor for bridge components or culverts in NBI ratings less than "6." Most bridges in the Florida inventory considered (2007 and 2008 inspections) are in NBI ratings “6” or higher, with roughly about 95% for each of the bridge components decks, superstructures, and substructures, and culverts. Given that there are fewer than about 5% of the bridges in the inventory with NBI condition ratings less than or equal to “5,” the results should be considered reasonably accurate for the overall bridge inventory. Calibration (with regression factors) of the original translated ratings was observed to significantly improve the accuracy of translation on individual bridge components, with most bridge with about 90% of the bridges having errors less than or equal to one.

The following additional general observations also were made during the study: state-maintained bridges can be better translated than other bridges; slabs should be considered as both deck and superstructure elements on the bridges; condition of substructures associated with culverts do not necessarily affect the overall condition index or NBI rating of the culvert; not all translation errors can be explained quantitatively; translation errors cannot be significantly related to bridge or roadway attributes; reasonable accuracy of translation was demonstrated using the element condition data and NBI condition data on Florida’s state-maintained bridges inspected in 2007 and 2008; and the proposed NBI Translator Program can be accurately used to develop deterioration models of the bridge components and the elements.

4. Deterioration and Action Effectiveness Models

This section describes the development of improved deterioration and action effectiveness models for Pontis and the Project Level Analysis Tool. Florida DOT began its Pontis implementation in 1998 and has element inspections on certain bridges dated as far back as 1995. Taking advantage of this 14 years of inspection and work accomplishment history with 884,678 individual element inspection records and 93,615 maintenance activity records, the agency has amassed sufficient data to develop statistically sound deterioration and action effectiveness models for its entire bridge inventory, including specialized elements for non-bridge structures, such as sign structures and retaining walls, and moveable bridge equipment.

4.1 Background

The Florida Department of Transportation (FDOT) has implemented the Pontis Bridge Management System, developed by the American Association of State Highway and Transportation Officials (AASHTO) and licensed by 45 states as well as local and national governments (Cambridge 2003). Pontis manages the Department's structure inventory and inspection data, and provides decision support for the planning of structure preservation, improvement, and replacement activities. Table 4.1 summarizes the structures included in the system at the time the initial database for this study was prepared in October 2008, on and off the state highway system. Additional non-bridge structures have since been added; however since they do not yet have two or more element inspections, they are not considered in this report.

Table 4.1. Number of structures covered by this analysis

Type	On-system	Off-system	Total
Bridge	4,914	4,639	9,553
Culvert	1,134	1,187	2,321
Tunnel	1	0	1
Sign structure	5,047	396	5,443
High-mast light pole	1,767	126	1,893
Mast arm	1	0	1
Retaining wall	1	0	1
Total	12,865	6,348	19,213

Decision support in Pontis uses a set of analytical models to evaluate project and program alternatives, in order to help decision makers optimize the scope and timing of structure work. It also assists in prioritizing and scheduling work, and allocating funding, across the structure inventory. To accomplish this, Pontis contains a set of forecasting models for cost, deterioration, and action effectiveness, all of which contribute to a capability to forecast life cycle costs. Florida has implemented the most up-to-date full version of Pontis, release 4.4. Subsequent releases have been updating the system to a new web-based technology platform, and adding new predictive models. FDOT is evaluating whether and when to implement the next planned full release, Pontis 5.2.

The Florida deterioration models in Pontis were first developed in an expert judgment elicitation process that took place in October 2000. At that time, FDOT lacked sufficient historical element inspection data to develop a statistically sound forecasting model. Pontis implementation with systemwide element inspections began in 1998, with some earlier inspections dating back as far as 1995. Now in 2009, the Department has a sufficiently large data set to estimate models based on historical data.

The analysis reported here draws on several widely-accepted concepts of bridge inspection and deterioration, used in Pontis as well as in many other bridge management systems worldwide. These are described in the following sections.

4.1.1 Element inspections

As a part of its routine bridge inspection process, Florida DOT gathers maintenance condition data on 151 standardized structural elements. Florida's inspection standards are based on the AASHTO CoRe Elements (AASHTO 2007), but also include a variety of non-bridge elements as well as a detailed breakdown of the electrical, mechanical, and hydraulic elements of moveable bridges. Examples of elements are: concrete deck with asphalt concrete overlay; prestressed concrete column or pile; elastomeric bearing; and galvanized high-mast light poles. A full list may be found later in Table 4.16 of this report.

Condition of each element is described using standardized condition states. As an example of condition state language, painted steel bridge girders are inspected by allocating their total length among five condition states, defined as follows:

1. *There is no evidence of active corrosion, and the paint system is sound and functioning as intended to protect the metal surface.*
2. *There is little or no active corrosion. Surface corrosion has formed or is forming. The paint system may be chalking, peeling, curling, or showing other early evidence of paint system distress but there is no exposure of metal.*
3. *Surface corrosion is prevalent. There may be exposed metal, but there is no active corrosion which is causing loss of section.*
4. *Corrosion may be present but any section loss due to active corrosion does not yet warrant structural review of either the element or bridge.*
5. *Corrosion has caused section loss and is sufficient to warrant structural review to ascertain the impact on the ultimate strength and/or serviceability of either the element or the bridge.*

The inspector records each element's condition as a vector of percents, as in Table 4.2.

Table 4.2. Example element inspection

Element: 107 – Painted steel open girder/beam
Environment: 3 – Moderate

State 1	State 2	State 3	State 4	State 5
69.5	25.5	5.0	0.0	0.0

All amounts in percent

Certain bridge elements have only 3 or 4 condition states in their definitions. For example, the condition state definitions for element 300, strip seal expansion joints, is:

1. *The element shows minimal deterioration. There is no leakage at any point along the joint. Gland is secure and has no defects. Debris in joint is not causing any problems. The adjacent deck and/or header is sound.*
2. *Signs of seepage along the joint may be present. The gland may be punctured, ripped or partially pulled out of the extrusion. Significant debris is in all or part of the joint. Minor spalls in the deck and/or header may be present adjacent to the joint.*
3. *Signs or observance of leakage along the joint may be present. The gland possibly has failed from abrasion or tearing. The gland has pulled out of the extrusion. Major spalls may be present in the deck and/or header adjacent to the joint.*

The definitions of condition states are significant in deciding whether two or more elements are sufficiently similar to be combined for estimation purposes. Combining of relatively uncommon elements is important in building up enough of a sample size to estimate a statistically valid model. But elements can be combined only if they have the same number of condition states and if their definitions are compatible.

4.1.2 Markovian deterioration models

Bridge deterioration in Pontis is forecast using a Markovian model. A Markovian model assumes that the probability of making a transition from one condition state to another depends only on the initial state, and not on age, past conditions, or any other information about the element. Thus, the model is expressed as a simple matrix of probabilities (Table 4.3).

Table 4.3. Example deterioration model

From	To state 1	State 2	State 3	State 4	State 5
State 1	93.6	6.4	0.0	0.0	0.0
State 2		92.0	8.0	0.0	0.0
State 3			91.1	8.9	0.0
State 4				98.7	1.3
State 5					100.0

All amounts in percent

In Table 4.3, the rows are condition states at the beginning of the year, and the columns are condition states one year later. A cross-sectional model like this is especially useful for structures whose lives can extend to 50-100 years or more, where a full time series data set is not obtainable.

A Markovian transition probability matrix is a special type of matrix with a number of desirable properties that make it easy to process. A well-formed transition probability matrix adheres to the following rules:

1. Square matrix – All transition probability matrices are square. For Pontis they must be either 3×3, 4×4, or 5×5.
2. Upper right triangular – Only the main diagonal and the upper right triangle of the matrix are allowed to have non-zero values. This is another way of saying that there can be no movement from any condition state to a better state in a deterioration model.
3. Non-negative – No elements of the matrix may be negative.
4. Positive diagonal – Elements on the diagonal must be non-zero. In other words, there must be a non-zero possibility of an element remaining in the same condition state from one inspection to the next.
5. Normalized – All rows of the matrix must separately sum to 100%. In other words, the transition probability matrix must account for all possible states of the element.
6. Because of the combination of these rules, the lower right corner element must be 100%. Once an element deteriorates to the worst condition state, it stays there.

Pontis defines a notional "failure" state and uses a "failure probability" as a part of the penalty for allowing elements to remain in states of advanced deterioration. Since the current analysis doesn't address the failure probability, elements that reach the worst normal condition state are assumed to remain there. Hence the 100% in the bottom row of each transition probability matrix.

Conditions in any future year can be predicted with a Markovian model by simple matrix multiplication. Mathematically, the matrix multiplication for Markovian prediction, when no maintenance action is taken, looks like this:

$$y_k = \sum_j x_j \, p_{jk} \text{ for all } k \tag{4.1}$$

where x_j is the probability of being in condition state j at the beginning of the year; y_k is the probability of being in condition state k at the end of the year; and p_{jk} is the transition probability from j to k. This computation can be repeated to extend the forecast for additional years.

It is possible to derive transition probabilities if the median number of years between transitions is known. Often this is an easier way to develop a deterioration model from expert judgment. It also provides a convenient means of computing, storing, and reporting transition probabilities derived from historical inspection data. If it takes *t* years for 50% of a population of elements to transition from state *j* to state *k=j+1*, and no other transitions are possible, then the one-year transition probabilities are:

$$p_{jj} = 0.5^{(1/t)} \text{ and } p_{jk} = 1 - p_{jj} \tag{4.2}$$

So if it takes a median of 10.23 years to transition from state 1 to state 2, then the probabilities after one year are 93.4% for state 1 and 6.6% for state 2.

4.1.3 Health index

Element condition state language is highly specific to individual components of structures, yet the general pattern of 3-5 condition states representing type and severity of deterioration, is common across all elements. This makes it possible to derive a relatively straight-forward procedure for characterizing overall condition of any facility made up of elements.

The Health Index was first proposed by the California Department of Transportation as a type of weighted average condition measure for a bridge or any subset of an inventory (Shepard and Johnson 2001). It includes all condition states, weighting each element by its replacement cost, failure cost, or by some other appropriate weight. This gives emphasis to elements that have the biggest economic or structural impact on bridge functionality. The Health Index is computed as follows:

$$\text{Health Index: } HI = \frac{CEV}{TEV} \times 100 \tag{4.3}$$

$$\text{Current Element Value: } CEV = \sum_e W_e \sum_j^{N_e} Q_{ej} \left(1 - \frac{j-1}{N_e - 1}\right)$$

$$\text{Total Element Value: } TEV = \sum_e W_e \sum_j^{N_e} Q_{ej}$$

where W_e is the element weight, usually replacement or failure cost for element *e*

Q_{ej} is the quantity of element *e* in condition state *j*

N_e is the number of condition states defined for element *e*

Health Index is essentially a weighted average of the percent of each element in each condition state, expressed on a scale of 0 (completely deteriorated) to 100 (like new). It has become widely used because it serves the useful purpose of digesting detailed element condition data into a simpler index of condition.

4.1.4 Change in condition

From one inspection to the next, the condition of each element on each bridge may change. Condition is made worse by time, weather, traffic, pollution, and operating conditions such as (in most states, though not Florida) the use of deicing chemicals. These factors promote physical and chemical processes that may increase the severity of material defects, or increase the extent of defects at any given severity level.

Mild deterioration may entail damage to protective systems, thus increasing the rate of deterioration of underlying structural materials: for example, paint damage leads to an increased rate of steel corrosion. Mild deterioration of a bridge deck or expansion joints may cause road user discomfort, or may affect safety or safe travel speeds. Mild deterioration can also cause an unsightly condition that negatively impacts nearby property values or causes customer or stakeholder dissatisfaction. More significant deterioration may cause a loss of functionality, such as the inability of a structural element to carry its designed loads.

Counteracting this normal deterioration and its impacts, the agency applies preservation actions intended to either improve condition, or at least slow the rate of deterioration. While deterioration can be observed every year, preservation actions occur infrequently, often at intervals of 10-30 years or more. Because of the substantial cost of mobilizing crews, equipment, and materials to a work site, and the inconvenience of work zones to the public, FDOT, like all agencies, strives to minimize the frequency of work activities by maximizing the durability of structural components and protective systems.

In Florida as in most states, each bridge is inspected by trained personnel on intervals averaging 2 years. The purpose of inspections is to document conditions and performance that may indicate a need for preservation, improvement, or replacement work. From one inspection to the next, an element's condition may change due to deterioration, agency actions, or both.

In order to estimate statistical models of deterioration and action effectiveness, it is necessary to separate the effect of deterioration from the effect of agency actions. These effects are not directly measured, but must be deduced from a limited amount of information in two snapshots of condition spaced 2 years apart, plus any available records of agency actions that may have been performed in between the two snapshots. Figure 4.1 shows the problem schematically. If an agency action occurred on the element between 2005 and 2007, then the percent of the element observed to be in state 3 in 2007 may be due to a combination of normal deterioration from states 1, 2, or 3; and the effect of agency action in improving parts of the element which may previously have been in states 3, 4, or 5.

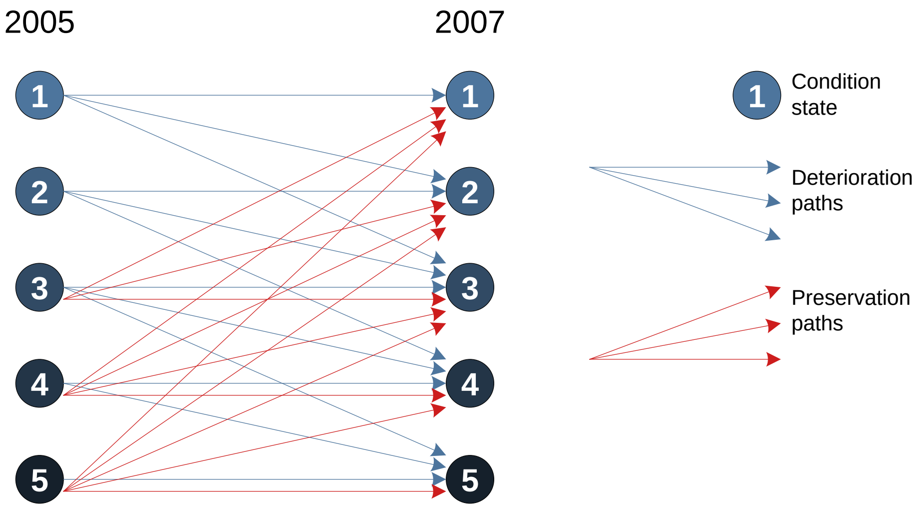


Figure 4.1. Changes in condition between two element inspections

Estimation of the deterioration model is a matter of quantifying the flows along the blue paths in Figure 4.1, while the effectiveness model comes from quantifying the red paths. As will be described later in this report, the deterioration paths occur between every pair of inspections on every element of every structure. In contrast, the red paths occur only in about 9% of the inspection pairs, because agency actions are relatively infrequent. The strategy pursued in this research, therefore, is as follows:

1. Identify a set of inspection pairs, in which there is reasonable confidence that no preservation activities have taken place. Estimate the deterioration model from these.
2. Identify a set of preservation activities, and compare element conditions before and after. From the change in condition, subtract the effect of deterioration. Averaged over all similar activities, this is the action effectiveness model.

One way to determine whether preservation activity has taken place between inspections, is to consult FDOT information systems where records of past activities are maintained. As will be described later, this is a useful, but imperfect, indication of the causes of condition improvements. An important factor limiting their usefulness is that such records are available only for state-maintained bridges. It was also noted that a large number of inspection pairs showed improvements in condition without a corresponding record of preservation activity. In fact, about 26% of the cases of condition improvement lacked corresponding activity data.

To study the completeness of maintenance records and identify inspection pairs possibly having preservation effects, a measure of condition improvement was developed, as follows:

$$CI_e = \max_{ej}\left(\sum_{k=1}^{j} y_k - \sum_{k=1}^{j} x_k\right) \tag{4.4}$$

where CI_e = condition improvement for element inspection pair e

j and k are condition states defined for element e

$\max_{ej}$ indicates maximization over all condition states defined for element e

y_k = fraction of the element in condition state k in the second inspection of the pair

x_k = fraction of the element in condition state k in the first inspection of the pair

Equation 4.4 quantifies improvement as the increase in the fraction at, or better than, any given condition state. Computed over all condition states, the largest increase is selected to represent the inspection pair as its maximum condition improvement. Under a pure deterioration scenario where there are no preservation paths, the improvement must be non-positive for every condition state, so CI also must be non-positive. (It could be zero or negative.)

If any one or more of the condition states shows an increase in the fraction at its level or better, then CI is positive. This can indicate either that an error occurred in the inspection process, or a preservation activity took place. As will be discussed later, an investigation found no evidence that inspection error was a significant factor in these observations, so therefore maintenance activity is presumed even if there is no record of it.

An alternative way to evaluate condition improvements in an element inspection pair is to use the health index as in Equation 4.3. If health index improves between the two inspections, then preservation activity could be presumed. However, as Table 4.4 shows by example, an inspection pair can show evidence of preservation even if its health index declines.

Table 4.4. Example of condition change in an inspection pair

Bridge 010029, Structure unit 1, Element 204 (Prestressed concrete column or pile), Environment 4 (Severe)

Inspection	State 1	State 2	State 3	State 4	HI	CI
01/23/2001	41.18	8.82	45.59	4.41	62.24	
01/21/2003	0.00	83.82	11.76	4.41	59.83	33.82

All amounts in percent

In Table 4.4, the maximum improvement occurs at state 2, where the percent at or above state 2 is higher in the second inspection by 33.82. However, the health index went down. This is due to a combination of deterioration and maintenance work. The maintenance work improved a portion of the element from state 3 to state 2, but in the meantime the portion previously in state 1 deteriorated to state 2. So even though health index deteriorated, there is strong evidence that maintenance work took place. On the other hand, it is not possible for HI to improve if CI is less than or equal to zero.

4.2 Data Preparation

Three primary data sets were used in the analysis described here: a Pontis database containing all inspections on all public bridges in Florida since 1995; all maintenance activity records since 1995 having a bridge identifier, from the FDOT Maintenance Management System (MMS); and all contract work activity records having a bridge identifier in FDOT's AASHTO Trns•Port database, from 2005 to 2009.

The Pontis database contains all element inspection data on Federal, state, county, and local bridges, as well as a variety of non-bridge structures such as high-mast light poles and sign structures, for a total of 19,213 structures. The work activity databases contain activities only on structures on the state highway system. For contract maintenance, the data set is further limited to the period when Trns•Port has been in use. A total of 11,019 structures are addressed in the MMS and Trns•Port data sets.

4.2.1 Preparation of inspection data

In order to estimate the Markovian models, a complete Pontis database was obtained from FDOT and imported to a desktop database manager. This database was first prepared in September 2008. It was subsequently refreshed in October 2009 to add the intervening year's inspections. The refresh did not add more structures, since new structures would not have more than one inspection and would not be useful in the analysis anyway.

Using Structured Query Language (SQL), the table of 884,678 element inspection records was transformed into 614,699 inspection pairs. Each inspection pair consists of two element inspections as in Table 4.4 above, both belonging to the same bridge, structure unit, element, and environment class, and spaced two years (± 6 months) apart. The two-year interval was chosen because most bridges in Florida are inspected on a two-year cycle.

Inspection pairs were filtered to remove inappropriate data, as follows:

- Both inspections in a pair must have the same quantity (e.g., sq.m of deck), the quantity breakdown by condition state must sum to the total quantity, and the quantity breakdown fields must be populated as dictated by the element definition.
- The first round of inspections, from a training period in the mid-1990s (with inspevnt.inspkey='STRT'), was removed.

The database was also checked for bridges belonging to district 9, which in Florida is a way of flagging deleted or obsolete bridge records. However, FDOT had already excluded these from the data set provided. The health indexes and condition improvements were calculated for each pair as described in Equations 4.3 and 4.4. Table 4.5 summarizes the number of inspection pairs.

Table 4.5 shows that about 9% of inspection pairs show some type of improvement indicating likely maintenance action. With an average inspection interval of 2 years, this is equivalent to one maintenance action affecting condition of a given element every 22 years. On-system bridges receive preservation activity somewhat more often than off-system bridges.

Table 4.5. Summary of Inspection Pairs

State Highway System	Inspection pairs (count)	Improved (count and percent)	Activity interval (years)
Off	234,471	19,443 (8.29%)	24.12
On	380,228	35,945 (9.45%)	21.16
Total	614,699	55,388 (9.01%)	22.20

4.2.2 Preparation of activity data

Work activity data sets were obtained from FDOT from the Maintenance Management System and from Trns•Port. A subset of these data, containing usable cost information, had previously been obtained by Florida State University for development of Pontis cost models. The additional data obtained for the deterioration and action effectiveness analysis included activity records that were not usable for cost modeling, but might be usable for deterioration and effectiveness. For use in deterioration modeling, each activity must have:

- A bridge identifier.
- A basis for estimating the date on which the work was completed, comparable to inspection dates.

For use in action effectiveness modeling, each activity must have the above items, plus a basis for estimating the type of action that was performed. A total of 93,615 activity records from the two systems satisfied these criteria.

It should be noted that for cost modeling, it is adequate to use a sample of work activity records and to filter data based on the quality of quantity and cost information. For deterioration, on the other hand, work activities are used for the purpose of eliminating inspection pairs from consideration. This makes it important to include any work activity that might cause changes in condition, even if very little is known about the activity. In other words, for cost analysis data quality is more important than quantity; while for deterioration analysis data quantity beats quality.

4.2.2.1 Estimation of activity date

For data in the Maintenance Management System, each work activity has either a contract completion date or a crew activity completion date, provided that the work was indeed completed. In some cases both dates are specified. These dates can be inexact when paperwork is done in batches over a large number of bridges and non-bridge activities. Florida's Trns•Port database has a contract letting date, but does not have a completion date usable for this analysis. Further investigation determined that the average completion date is about two years following the letting date, but this can vary widely. The reason these dates are important, is that it is necessary to identify the last inspection prior to the work, and the first inspection after the work, in order to determine the change in condition that may have been caused by the work.

One way to improve the quality of the estimated completion date, is to examine inspection data near the initial estimate of completion date, to see if the expected improvement in condition did occur. If an improvement in condition was not found at the time of the initial estimated completion date, then the next inspection intervals earlier and later were checked. For MMS activities, earlier dates were checked as long as they were on or after the request date for the work item; for Trns•Port activities, earlier dates were checked as long as they were on or after the letting date. For both systems, later dates were checked as long as they were within 2 years of the initial estimated completion date.

An algorithm was developed to automate this investigation for all 93,615 activity records in the data set. If the initial estimate of completion date did not correspond to an improvement in condition, but another nearby inspection interval showed the expected improvement, then the estimated completion date was changed accordingly. The completion date was left unchanged if no nearby inspections showed improvement. The algorithm was designed to maximize the number of condition improvements that are associated with a work activity, while minimizing the magnitude of changes to estimated completion dates. Table 4.6 summarizes the results of the analysis. Activities that did not show any improvement in condition typically were routine maintenance actions that would not be expected to improve condition (such as brush clearing, mechanical adjustments, or cleaning); or activities that were requested but not actually completed. Activities that took place outside the date range of element inspections on the structure were not used in the analysis since their effect on condition could not be determined.

Table 4.6. Summary of results of the completion date estimation algorithm

Count	Result
31,335	activities with improved condition consistent with the initial estimated completion date
1,772	activities whose completion dates were moved earlier than the initial estimate
5,858	activities whose completion dates were moved later
1,248	activities on structures that have not yet had their second element inspection
16,680	activities that took place before the first element inspection on the structure
16,743	activities on structures that have not yet been inspected since the activity took place
13,337	activities did not show any improvement in condition
6,642	activities had an invalid or non-existent bridge identifier
93,615	total activity records

Overall, 52,302 activity records were available for the deterioration analysis, based on their estimated completion date. Of these, 38,965 (74.4%) improved the condition of the structure as reflected in element inspections. Table 4.7 explores the relationship between improved inspection pairs, and identified activities. For on-system bridges, 75.42% of inspection pairs showing improvement, had activity records for the same bridge and date range as the inspection pair. Off-system bridges, on the other hand, had very little support from maintenance activity records.

Table 4.7. Summary of inspection pairs

State Highway System	Pairs with improvement (count)	Improved pairs having activities (count and percent)
Off	19,443	1,931 (9.93%)
On	35,945	27,108 (75.42%)
Total	55,388	29,039 (52.43%)

Narrowing further, the domain of the Trns•Port data set is state highway bridges in 2005 and later, a period also covered by MMS. In this period there are 13,490 inspection pairs showing improvement, of which 10,280, or 76.20% are associated with activity records. This indicates that the addition of Trns•Port data improves the coverage only slightly. As a result of this observation, it was decided to use the entire timeframe of Pontis element inspections even though Trns•Port data are available for only the final four years of it.

4.2.2.2 Cause of condition improvements

If 75.42% of element condition improvements can be associated with maintenance activities, then this begs the question of what causes the remaining 24.58% of condition improvements. Possible causes are unrecorded maintenance, improvement, or replacement activities; or inspection errors. An analysis was conducted to see if any information available about inspection pairs might shed light on whether an activity was performed. This is necessary in order to determine whether to exclude these unexplained condition improvements from the deterioration model. It is also necessary in order to decide how to screen inspection pairs on off-system bridges.

One way to approach the question is to stratify condition improvements according to the magnitude of the improvement, using ranges of CI in Equation 4.4. If random inspection error has a significant role, then such errors should be distributed around the true, deteriorated condition levels according to a normal distribution. The effect would be that the unexplained improvements should have small values of CI clustered around zero. Larger condition improvements then should be associated with identified activity records at a higher rate than the average of 75.42%.

Figure 4.2 shows this comparison for bridges on the state highway system. The "known activity" line shows how the magnitude of condition improvement affects the percent explainable by identified maintenance actions. Across the entire range of condition improvement, it remains relatively constant near its average of 75.42%. This is not consistent with the hypothesis that random inspection error might be a cause of the unidentified condition improvements.

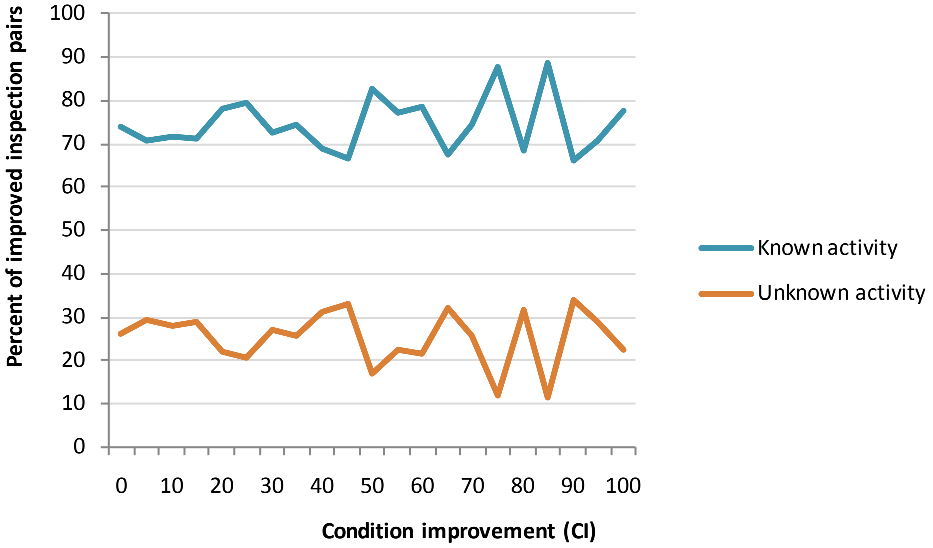


Figure 4.2. Comparison of inspection pairs with known and unknown activities

Other possible explanatory variables were also investigated, including element category, element material, year the bridge was built, design type, and district. Design type and district had the most significant differences, as reported in Table 4.8. However, the differences were not significant enough to provide guidance on how to handle condition improvements with unknown causes.

Table 4.8. Breakdown of percent of improved inspection pairs having identified activity records

Design type	Improvements (count)	Percent with activities	District	Improvements (count)	Percent with activities
Movable bridge	12,225	94.90	1	4,491	74.91
Other bridge	18,233	68.37	2	8,275	86.38
Culvert	1,315	56.58	3	1,707	65.79
Sign structure	4.101	55.06	4	7,973	76.38
High-mast light pole	71	54.93	5	4,769	71.40
			6	3,004	48.00
			7	5,184	80.50
			8	542	66.97

The conclusion of this analysis is that the unexplained condition improvements are likely caused by unreported preservation, improvement, or replacement activity. As a result, it was decided to exclude the unexplained condition improvements from the deterioration model estimation process.

4.2.2.3 Estimation of type of work performed

Both MMS and Trns•Port record the bridge ID of structures receiving maintenance work. However, neither system records the specific bridge element and preservation action in a manner compatible with Pontis. In the Maintenance Management System, most activities are coded with a general activity code, having just a few values related to bridges. The codes are shown in Table 4.9.

Table 4.9. MMS bridge-related activity codes

Code	Count	Description
805	8,269	Bridge Joint Repair
806	11,792	Bridge Deck Maintenance And Repair
810	4,227	Bridge Handrail Maintenance And Repair
825	7,241	Superstructure Maintenance And Repair
845	19,741	Substructure Maintenance And Repair
859	3,489	Channel Maintenance
861	4,768	Routine Bridge Electrical Maintenance
865	2,943	Routine Bridge Mechanical Maintenance
869	2,527	Movable Bridge Structural Maintenance
888	150	Bridge Damage Repair
898	27	Tunnel Maintenance

Other codes may also occur on bridges, but their definition is not specifically bridge-related

Since Florida's Pontis database has 822 do-something preservation action codes for all the possible elements and condition states, it is evident that the MMS classification is much less detailed. To help bridge the gap, the FDOT 2001 cost model study (Sobanjo and Thompson 2001) developed a system of action categories and sub-categories that aggregate similar Pontis action codes. These are shown in Table 4.10.

For the current study, this system is still valid. Each of the 822 Pontis preservation actions was assigned to one of the 48 action sub-categories. Action effectiveness models were ultimately developed for each sub-category, and then used by all of the corresponding Pontis actions.

Since the MMS activity codes are not detailed enough to identify action sub-categories, it was necessary to look for other clues in the activity data set.

One important clue is that the action sub-category must be defined for elements and condition states that actually occur on the bridge. An algorithm was developed to find the element inspections that occurred immediately before each activity, and list the elements and their condition states having non-zero quantities. Each element/state has a list of feasible Pontis actions, each of which is associated with an action subcategory. By following this chain of correspondences, it was possible to make a complete list of valid action subcategories for a given activity.

Table 4.10. Action sub-category system

			Action Category			
		Object	100-Replace	200-Rehab	300-Repair	400-Maint
Materials	0	Other material				400 (1)
	1	Deck	101	201 (2)	301 (3)	401 (4)
	2	Steel/coat (incl metal)	102 (5)	202	302 (6)	402 (7)
	3	Concrete		203	303 (8)	403 (9)
	4	Timber		204		404
	5	Masonry		205		405
	6	MSE		206		406
Hi-Maint	10	Other element				
	11	Joint	111	211	311	411
	12	Joint seal	112			
	13	Bearing (incl p/h)	113	213		413
	14	Railing	114			
Drainage	21	Slope prot	121	221		
	22	Channel		222		422
	23	Drain sys	123	223		423
Machinery	31	Machinery	131 (10)	231 (10)	331 (10,11)	431 (10)
	32	Cath prot	132			
Major	41	Beam	141			
	42	Truss/arch/box	142			
	43	Cable	143	243		
	44	Substr elem (exc cap)	144 (12)			
	45	Culvert	145			
	46	Appr slab	146	246 (13)		
Appurtenances	51	Pole/sign	151			

White cells represent valid sub-categories; numbers in parentheses refer to footnotes

Footnotes

1. Wash structure
2. Rehab deck and replace overlay
3. Repair deck and substrate
4. Repair potholes
5. Replace paint system
6. Spot paint
7. Restore top coat
8. Clean rebar and patch
9. Patch minor spalls
10. Incl. elec, hydraulic, and mech elements
11. Repair and lubricate
12. Incl. fenders, dolphins, and pile jackets
13. Mudjacking

To further narrow the list to a single sub-category, a scoring system was developed. The scoring system has several elements:

- Each valid action sub-category has an initial score of 1.0.
- If an element's condition showed any improvement according to equation 4.4, then its corresponding action sub-category scores were multiplied by 1.5.
- A subset of 15,274 activities had been given manually-assigned action sub-categories as a part of the earlier cost model analysis by Florida State University. If the manually-assigned sub-category was on the list of action sub-categories corresponding to elements that improved in condition, then the manually-assigned action sub-category was selected and the procedure terminated at that point. Otherwise, the manually-assigned sub-category was checked against the list of sub-categories that are valid for the activity and, if valid, was given an additional multiplier of 1.5.
- A correspondence table was developed between MMS activity codes and similar action sub-categories. Sub-categories that are associated with the activity's MMS activity code were given an additional multiplier of 1.5.
- Most activities in the data set have textual descriptions of the work that was done. A dictionary was created of 2,038 significant words that occur in these descriptions. The dictionary includes abbreviations and misspellings found in the data set. Each word in the dictionary was assigned to a list of relevant action sub-categories, and given a score to represent the importance of the word in narrowing the list of possible sub-categories. For each activity, the textual description was processed using the dictionary, building up a score for each valid sub-category. Words near the beginning of the description were given a slightly higher weight, this acting as a tie-breaker.

None of these clues by itself was able to uniquely assign a sub-category to an activity, but the combination of them was sufficient. The scoring algorithm was validated against the manually-assigned subset, then applied to the full activity data set to assign action sub-categories to all activities having valid completion dates. The total number of activities assigned to each action sub-category are shown in Table 4.11.

4.2.2.4 Usability of activities in model estimation

Ideally, it would be desirable if the data set of inspection pairs used in estimation of the deterioration model, were filtered only by excluding pairs corresponding to known maintenance activities. However, this is not possible in the current study because of the number of unexplained condition improvements, especially for off-system structures.

Table 4.11. Summary of activities found in each action sub-category

Action sub-category		Count	Action sub-category		Count
101	Replace deck	11	221	Rehab slope protection	417
102	Replace paint system	3086	222	Rehab channel	833
111	Replace joint	1099	223	Rehab drainage system	1
112	Replace joint seal	1547	231	Rehab machinery	688
113	Replace bearing	102	246	Mudjacking	752
114	Replace railing	144	301	Repair deck and substrate	553
121	Replace slope protection	454	302	Spot paint	3556
123	Replace drainage system	52	303	Clean rebar and patch	5929
131	Replace machinery	2073	311	Repair joint	1205
132	Replace cathodic protection	649	331	Repair/lubricate machinery	1592
141	Replace beam	40	400	Wash structure	2406
144	Replace substructure element	236	401	Repair potholes	2264
145	Replace culvert	13	402	Restore top coat	6461
146	Replace approach slab	297	403	Patch minor spalls	9158
151	Replace pole/sign	4	404	Maintain timber	5
201	Rehab deck/replace overlay	45	405	Maintain masonry	424
202	Rehab steel	293	406	Maintain MSE	271
203	Rehab concrete	838	411	Maintain joint	1118
204	Rehab timber	72	413	Maintain bearing	212
205	Rehab masonry	100	422	Maintain channel	117
206	Rehab MSE	73	423	Maintain drainage system	184
211	Rehab joint	156	431	Maintain machinery	2074
213	Rehab bearing	144	446	Maintain approach slab	554

The benefit of excluding a large number of inspection pairs, even those where maintenance activity is not known for sure to have occurred, is that it reduces the possibility of upward bias in the deterioration models caused by the possible maintenance actions. The disadvantage of excluding a large number of inspection pairs is that it reduces the sample size available to the estimation process, making it more difficult to achieve statistically valid models.

As a reasonable balance of these considerations, it was decided at first that the following exclusions would be applied to screen the inspection pairs:

- Remove all inspection pairs that show improvement in condition as evidenced by a positive value of CI (Equation 4.4).
- Additionally, remove all inspection pairs corresponding to identified activities.

The latter criterion was determined by searching for activities on the same structure with completion dates between the two inspection dates of the pair, where the action sub-category of the activity is valid for the element of the inspection pair. This had the effect of removing inspection pairs where there is a possibility that work occurred even though conditions did not improve. Only activities with valid completion dates were used in the second criterion. Activities in action category 400 were not used, since minor maintenance actions are not expected to affect condition. A total of 27,054 activities meet these criteria.

In the data set of inspection pairs, the initial list of 614,699 pairs was reduced by 55,388 by the first criterion, and by an additional 66,830 pairs by the second criterion. The model estimation process described in Section 4.3 was conducted first for the full data set with no exclusions (n=614,699). Then the first exclusion was added (n=559,311), and then the second (n=492,481). The first exclusion had a modest effect on the results, changing the average decay time by less than 2%, and having a negligible effect on statistical validity. The second exclusion changed average decay time by an even smaller amount, less than 1%, but caused four of the 72 final models to violate the thresholds of statistical validity. From this full-scale test, it was finally decided to use only the first exclusion in the final results. For the action effectiveness model, an activity is included in the analysis only if it has a valid completion date, a valid action sub-category, and is identified with at least one inspection pair where conditions improved and where the action sub-category is valid for an element that improved. There are 27,779 such activities.

4.3 Estimating Transition Probabilities

A separate Markovian transition probability matrix was estimated for each of the 151 elements, for each of 4 environments. While many of the models had generous sample sizes, others did not. So composite models were also estimated for categories of elements and material types, in order to create larger models for groups of similar elements. A set of models was produced for each environment, plus one more set that combined all four environments. For each model, a matrix of estimated transition probabilities was produced, if possible. Each matrix was also converted to an equivalent estimate of the median transition time between states, using the inverse of equation 4.2:

$$t = \frac{\log(0.5)}{\log(p_{jj})} \tag{4.5}$$

To aid in model evaluation, each matrix was further condensed by calculating the *decay life*, the median number of years for an element starting in perfect condition, to deteriorate to a point where 50% had reached the worst defined condition state. This was done by applying equation 4.1 iteratively until the probability of the worst state reached 50%.

To evaluate model performance, a coefficient of determination (r^2) was computed. The transition matrix was applied to the first inspection of each pair, to yield a prediction of the second inspection. The prediction and the actual values were converted to health indexes, using Equation 4.3. Then r^2 was computed by comparing these values as follows:

$$r^2 = 1 - \frac{SS_e}{SS_t} \tag{4.6}$$

$$SS_e = \sum_i (y_i - f_i)^2$$

$$SS_t = \sum_i (y_i - \bar{y})^2 \qquad \bar{y} = \frac{1}{n} \sum_i y_i$$

where i is an index over the list of inspection pairs used in the analysis
y_i is the health index calculated directly from the second inspection in the pair
f_i is the health index calculated from the prediction of the second inspection
n is the total number of inspection pairs

This provided a measure of how much of the variation in the second inspection of each pair, was explained by the model. The model estimation and evaluation process was automated using Microsoft

Excel and Visual Basic for Applications (VBA). Two different methods were developed and compared, as described in the next two sections. All together, 2660 models were created and evaluated.

4.3.1 Regression Method

Pontis has a built-in method for estimating transition probability matrices from historical inspection data (Cambridge 2003). For the present study, an adaptation of this method was used. The method uses linear algebra to combine two vectors:

Conditions at the beginning of the period:

$$[\mathrm{X}] = \{x_1^i, x_2^i, x_3^i, x_4^i, x_5^i\} \text{ for all inspection pairs i} \tag{4.7}$$

Conditions at the end of the period:

$$[\mathrm{Y}] = \{y_1^i, y_2^i, y_3^i, y_4^i, y_5^i\} \text{ for all inspection pairs i} \tag{4.8}$$

These are the known values in the estimation equation. The prediction equation is:

$$[\mathrm{Y}] = [\mathrm{P}][\mathrm{X}] \tag{4.9}$$

where [P] is the transition probability matrix. The unknown transition probabilities can be estimated:

$$[\bar{\mathrm{P}}] = [\mathrm{XX}]^{-1}[\mathrm{XY}] \tag{4.10}$$

Matrix of XX sums:

$$[\mathrm{XX}] = \textstyle\sum_i x_j^i x_k^i \text{ for all combinations of j and k} \tag{4.11}$$

Matrix of XY sums:

$$[\mathrm{XY}] = \textstyle\sum_i x_j^i y_k^i \text{ for all combinations of j and k} \tag{4.12}$$

The exponent on $[XX]^{-1}$ indicates matrix inversion. Following the regression computation, the resulting matrix is normalized to ensure that it satisfies the rules of a well-formed transition probability matrix. Any values to the left of the diagonal are set to zero. If any diagonal elements are less than 0.01, they are changed to 0.01. Negative values to the right of the diagonal are set to zero. Then each row is adjusted to sum to 1.0:

$$p'_{jk} = \frac{p_{jk}}{s_j} \qquad\qquad s_j = \sum_k p_{jk} \tag{4.13}$$

Since the inspection pairs all have an interval of two years, the result must be transformed to show the probabilities in one year, by finding its square root. The square root [Q] of a matrix [P] is the value of [Q] such that [Q][Q]=[P]. In other words, if [Q] is a one-year matrix equivalent to a two-year [P], then normal matrix multiplication as typically used in a Markovian model should convert [Q] to [P]. Fortunately, well-formed transition probability matrices have a closed-form solution to finding any root, such that matrix multiplication exactly reverses it. The square root of a 4x4 transition probability matrix is computed algebraically as follows:

$$\sqrt[2]{[P]} = [Q] = \begin{bmatrix} q_{11} & q_{12} & q_{13} & q_{14} \\ 0 & q_{22} & q_{23} & q_{24} \\ 0 & 0 & q_{33} & q_{34} \\ 0 & 0 & 0 & q_{44} \end{bmatrix} = \begin{bmatrix} \sqrt[2]{p_{11}} & q_{12} & q_{13} & 1 - q_{11} - q_{12} - q_{13} \\ 0 & \sqrt[2]{p_{22}} & q_{23} & 1 - q_{22} - q_{23} \\ 0 & 0 & \sqrt[2]{p_{33}} & 1 - q_{33} \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4.14}$$

$$q_{12} = \frac{p_{12}}{q_{11} + q_{22}} \qquad q_{23} = \frac{p_{23}}{q_{22} + q_{33}} \qquad q_{13} = \frac{p_{13} - q_{12}q_{23}}{q_{11} + q_{33}}$$

Following this operation, the matrix must again be normalized according to Equation 4.13. Table 4.12 shows an example of the regression results. A strong point of the regression method is that it can estimate the probabilities of transition from any starting state to any worse state. The upper-right triangle of the matrix can consist of all positive numbers. A weakness of the method is that it is subject to a variety of numerical problems with the matrix inversion step, which can yield incorrect results or failure to produce a result.

Table 4.12. Example result of regression method

Element 107 – Painted steel open girder/beam
All environments

From	To state 1	State 2	State 3	State 4	State 5
State 1	93.5	4.9	1.2	0.4	0.0
State 2		96.7	2.5	0.9	0.0
State 3			97.2	2.7	0.1
State 4				99.5	0.5
State 5					100.0

All amounts in percent; n=4947; r^2=0.761

4.3.2 One-step method

The regression method can be simplified by taking advantage of the typical two-year inspection period and one-year transition period. Since bridges deteriorate slowly, not much happens in such a short time. If p_{13} and all other elements non-adjacent to the diagonal are assumed to be zero, as in Table 4.3, then it is a *one-step* transition matrix.

To set up the estimation of a one-step matrix, the prediction equation (4.9) is defined as follows:

$$\begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \end{bmatrix} = \begin{bmatrix} p_{11} & p_{12} & 0 & 0 \\ & p_{22} & p_{23} & 0 \\ & & p_{33} & p_{34} \\ & & & p_{44} \end{bmatrix}^2 \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} \tag{4.15}$$

The element inspection vectors [Y] and [X] are spaced two years apart, but the transition probability matrix [P] is expressed for a one-year transition. Hence, it is applied twice. Writing out the individual equations necessary to calculate [Y] results in:

$$\begin{aligned} y_1 &= x_1 p_{11} p_{11} \\ y_2 &= x_1 p_{11} p_{12} + x_1 p_{12} p_{22} + x_2 p_{22} p_{22} \\ y_3 &= x_1 p_{12} p_{23} + x_2 p_{22} p_{23} + x_2 p_{23} p_{33} + x_3 p_{33} p_{33} \\ y_4 &= x_2 p_{23} p_{34} + x_3 p_{33} p_{34} + x_3 p_{34} p_{44} + x_4 p_{44} p_{44} \end{aligned} \tag{4.16}$$

Since the sum of each row in [P] must be 1.0, the following additional equations apply:

$$p_{12} = 1 - p_{11}; \qquad p_{23} = 1 - p_{22}; \qquad p_{34} = 1 - p_{33} \tag{4.17}$$

The vectors [X] and [Y] can be computed from the database of inspection pairs to describe the combined condition of the element before and after. So these quantities are known. Thus the system of seven equations and seven unknowns can be solved algebraically for the elements of [P]. First find p_{11} from equation 4.16, then find p_{12} from equation 4.17, then p_{22} and p_{23}, and so on in a simple sequence.

A complication arises because the equations are second-order polynomials in p_{ii}, so it is necessary to use the quadratic equation to find the roots. For example, the equation for p_{33} is:

$$p_{33} = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \tag{4.18}$$

$$a = x_3; \qquad b = x_2 p_{23}; \qquad c = x_1 p_{12} p_{23} + x_2 p_{22} p_{23} - y_3$$

The same pattern of equations and solution methods apply to elements having 3 or 5 condition states as well. Each same-state transition probability p_{ii} is constrained to be in the range from 0 to 1 exclusive. Even though the quadratic equation finds two roots, in practice only zero or one root are in the necessary range. Out of 755 element-level models, only 4 found zero roots.

Table 4.3 above was produced by the one-step method for the same element as Table 4.12, so it is useful to compare them. Even though the one-step method is simpler, it still produced very nearly the same r^2 value, 0.758.

4.3.3 Model evaluation

Both the regression and one-step models impose certain requirements on the input data in order to work correctly. All condition states in the [*X*] and [*Y*] vectors must be occupied.

$$x_j > 0 \text{ and } y_j > 0 \text{ for all condition states } j \tag{4.19}$$

Also, there must be a continuous path of deterioration from the best to worst state, which can be expressed mathematically as:

$$\sum_{k=1}^{j} y_k < \sum_{k=1}^{j} x_k \text{ for all condition states } j \tag{4.20}$$

Out of 755 element-level models, 116 lacked any relevant inspection pairs for the corresponding element/environment; 171 violated Equation 4.19, and 173 violated Equation 4.20. Of the remaining 295 models, Table 4.13 summarizes the performance.

Table 4.13. Performance of element-level models

Problem	Regression model	One-step model
Transition times too long*	162	26
Transition times too short*	1	13
Weighted average r^2	0.7213	0.7217
Usable models	172	253

*Transitions <1 year or > 200 years by equation 4.5. Certain models had more than one.

This information suggests a number of conclusions to guide further refinement of the models:

- Even in a very large data set of 559,311 inspection pairs, most of the elements did not have sufficient data to estimate a usable model.
- Most of the regression models that produced quantitative results, failed to produce reasonable results. Further examination of the intermediate results showed that numerical instability (a wide range of solutions having the same explanatory power) was probably the cause.
- In spite of the added assumptions inherent in the one-step model, explanatory power (r^2) stayed basically the same.

When the sample sizes of the 755 models are sorted in descending order, the top model has 45,560 inspection pairs. The 172nd highest sample size is 1,403, giving an idea of the number of element inspection pairs required in order to produce a usable regression model. The 253rd highest sample size is 463, giving an idea of the sample needed for the one-step method.

For the one-year forecasting period of Pontis, the one-step method is clearly more robust than regression. This conclusion is not necessarily applicable to other bridge management systems, however. If a bridge management system has a longer inspection period, it is likely that fewer elements would violate Equations 4.19 and 4.20. With bigger changes from one inspection to the next, fewer numerical stability problems would arise. If the prediction period is also longer than one year, then the one-step model might be inappropriate, and a multi-step regression model might be more suitable.

4.3.4 Model refinement

In order to generate a more complete set of models, the individual element/environment models were grouped, and their data sets pooled. Collapsing the environment classes turned 755 models into just 151 models, but still only 86 of those models were usable in the one-step method. The models were further collapsed by grouping them into element types. The elements within each new element type share the following characteristics:

- The same number of condition states with the same or similar definitions.
- Similar transition times, or good intuitive reason to expect that they would be similar (e.g., similar materials and exposure).
- When combined, a sufficient sample size to expect a usable model.
- Elements were not combined with others if they had significant sample sizes and reasonable results on their own.

The final models reported later in this report (Table 4.19) are based on collapsing the 151 elements into 72 element types (Table 4.16), and collapsing the four environments into just one. All but one of these models had reasonable results. The combined coefficient of determination, r^2, averaged 0.73, a small improvement over the separate models. Sample sizes of the pooled data sets ranged from 493 to 45,560.

4.3.5 Environment factors

Florida mainly uses three of its environment categories, using the first one ("benign") only rarely (possibly erroneously). By collapsing the environment categories, the models lose the sensitivity to climatic, site-specific, and operational factors (e.g., marine location and air pollution) that might affect the rate of deterioration.

To regain this sensitivity, models were estimated at higher levels of aggregation (element category, material, and systemwide), but separately by environment as well as combined across environments. For each model, a decay life was calculated as the median total length of each deterioration model. Table 4.14 shows the average decay life for each environment and for the whole inventory. The ratio of the two can be called the environment factor.

Table 4.14. Decay lives and environment factors

	Envt 1 Benign	Envt 2 Low	Envt 3 Mod	Envt 4 Severe	All
Decay life (years)*	185	66	77	64	68
Environment factor	2.72	0.96	1.13	0.93	
Sample size	2,414	80,238	258,572	218,087	559,311
R-squared	0.54	0.79	0.75	0.72	0.75

*For elements starting in perfect condition, number of years for 50% to reach the worst defined condition state

It is interesting to note that the "Moderate" environment has slightly slower deterioration than the "Low" environment, which differs from typical expectations for these classes. Also, environments 2 through 4 are more similar to each other than is usually expected. The analysis leading to Table 4.14 was broken out by element category and by element material. The same pattern among environments occurred across these breakdowns as well.

4.3.6 Comparison with expert elicitations

Agencies that lack historical bridge inspection data typically develop interim models using an expert judgment elicitation process (Cambridge 2003). Such an exercise was completed in Florida in 2001. A panel of experts is asked the following question:

> *If 100 typical units of this element are in this state today, after how many years will 50 units have deteriorated to the indicated (next-worse) condition state, with the remaining 50 units still in today's state, if no action is taken?*

Typically the panelists answer the questions individually based on their own personal experience, then they discuss their answers and are given the opportunity to change them. An average of all responses becomes the median transition time for input to equation 4.2.

It has been speculated in the literature (Patidar et al. 2007) that these expert elicitations may overstate the probability of deterioration (or understate the transition time). The reason often given is that humans tend to remember more easily the things that change, than the things that don't change. Up until now there has been no way of testing this hypothesis.

Table 4.15 compares average transition times for the new models, to the average transition times in the 2001 expert elicitation models. It shows that the hypothesized effect is likely confirmed, and that it is very significant. Historical transition times are, on average, 1.97 times what the expert panelists thought. This finding could provide strong motivation for other states to re-examine their deterioration models if they have the data to support it.

Table 4.15. Ratio of new transition times to old expert judgment models

By element category*		By element material*	
Joints	3.2	Unpainted steel	1.8
Railing	1.6	Painted steel	1.9
Superstructure	1.7	Prestressed concrete	1.7
Bearings	2.2	Reinforced concrete	2.1
Substructure	2.0	Timber	1.8
Movable bridge equip	1.8	Other material	2.1
Channel	1.4	Decks	1.9
Other elements	1.4	Slabs	3.3
By condition state**		By environment**	
From state 1 to 2	1.8	Benign	2.2
From state 2 to 3	2.6	Low	2.6
From state 3 to 4	3.8	Moderate	2.7
From state 4 to 5	6.1	Severe	2.9

Unweighted averages over the elements in each category, considering only usable models as defined in Section 4.3

* Based on decay life

** Based on state-to-state transition times

Table 4.16. Assignment of elements to element types

ID	Type	Sample	Element name	ID	Type	Sample	Element name
12	A1	15710	Concrete Deck - Bare	312	E2	335	Enclosed/Concealed Bearing
13	A1	2508	Concrete Deck - Unprotected w/ AC Overlay	313	E2	6658	Fixed Bearing
28	A4	2188	Steel Deck - Open Grid	314	E2	826	Pot Bearing
29	A4	1633	Steel Deck - Concrete Filled Grid	315	E2	4	Disk Bearing
30	A4	169	Steel Deck - Corrugated/Orthotropic/Etc.	320	A6	17	P/S Concrete Approach Slab w/ or w-o/AC Ovly
31	A5	2485	Timber Deck - Bare	321	A6	38417	Reinforced Conc Approach Slab w/ or w/o AC Ovly
32	A5	197	Timber Deck - w/ AC Overlay	330	C1	1453	Metal Bridge Railing - Uncoated
38	A2	4764	Concrete Slab - Bare	331	C3	24827	Reinforced Conc Bridge Railing
39	A2	2088	Concrete Slab - Unprotected w/ AC Overlay	332	C4	889	Timber Bridge Railing
54	A5	12	Timber Slab	333	C5	11238	Other Bridge Railing
55	A5	45	Timber Slab - w/ AC Overlay	334	C2	5075	Metal Bridge Railing - Coated
98	A1	846	Concrete Deck on Precast Deck Panels	356	S1	224	Steel Fatigue
99	A3	4785	Prestressed Concrete Slab (Sonovoid)	357	S1	226	Pack Rust
101	D1	3	Unpainted Steel Closed Web/Box Girder	358	S1	255	Deck Cracking
102	D2	406	Painted Steel Closed Web/Box Girder	359	S1	142	Soffit of Concrete Deck or Slab
104	D6	297	P/S Conc Closed Web/Box Girder	360	S1	158	Settlement
105	D7	38	Reinforced Concrete Closed Webs/Box Girder	361	S1	898	Scour
106	D1	86	Unpainted Steel Open Girder/Beam	362	S1	230	Traffic Impact
107	D2	4947	Painted Steel Open Girder/Beam	363	S1	384	Section Loss
109	D6	15321	P/S Conc Open Girder/Beam	369	S1	463	Substructure Section Loss
110	D7	1690	Reinforced Conc Open Girder/Beam	370	S1	134	Alert
111	D8	2660	Timber Open Girder/Beam	386	I3	151	Fender Dolphin System Metal Uncoated
112	D1	11	Unpainted Steel Stringer	387	I3	1737	Fender Dolphin System Prestressed Concrete
113	D3	1991	Painted Steel Stringer	388	I3	20	Fender Dolphin System Reinforced Concrete
116	D7	1	Reinforced Conc Stringer	389	I3	870	Fender Dolphin System Timber
117	D8	16	Timber Stringer	390	I3	18	Fender Dolphin System Other Material
120	D1	4	Unpainted Steel Bottom Chord Thru Truss	393	I3	624	Bulkhead/Seawall Metal Uncoated
121	D4	737	Painted Steel Bottom Chord Thru Truss	394	I4	9936	Abutment Slope Protection Reinforced Concrete
125	D1	5	Unpainted Steel Thru Truss (excl. bottom chord)	395	I5	2755	Abutment Slope Protection Timber
126	D5	753	Painted Steel Thru Truss (excl. bottom chord)	396	I6	16353	Abutment Slope Protection Other Material
131	D4	25	Painted Steel Deck Truss	397	I7	497	Drainage System Metal Coated
135	D8	1	Timber Truss/Arch	398	I7	1480	Drainage Sytem Other Material
140	D1	11	Unpainted Steel Arch	399	B6	757	Other Expansion Joint
141	D5	8	Painted Steel Arch	474	J1	792	Wingwall/Retaining Wall Metal Uncoated
143	D6	0	P/S Conc Arch	475	J2	30918	Wingwall/Retaining Wall Reinforced Concrete
144	D7	81	Reinforced Conc Arch	476	J3	3325	Wingwall/Retaining Wall Timber
146	D1	5	Cable - Uncoated (not embedded in concrete)	477	J4	951	Wingwall/Retaining Wall Other Material
147	D2	63	Cable - Coated (not embedded in concrete)	478	J5	2995	Mechanically Stabilized Earth Wall
151	D1	9	Unpainted Steel Floor Beam	487	K1	8044	Overlane Sign Structure Horizontal Member Metal Co
152	D2	1834	Painted Steel Floor Beam	488	K1	9303	Overlane Sign Structure Vertical Member Metal Coat
154	D6	9	P/S Conc Floor Beam	489	K1	12008	Overlane Sign Structure Foundation
155	D7	44	Reinforced Conc Floor Beam	495	K1	850	High Mast Light Poles Metal Uncoated
156	D8	5	Timber Floor Beam	496	K1	87	High Mast Light Poles Metal Coated
160	D1	3	Unpainted Steel Pin and/or Pin and Hanger Assembly	497	K1	504	High Mast Light Poles Galvanized
161	D2	23	Painted Steel Pin and/or Pin and Hanger Assembly	498	K1	2	High Mast Light Poles Other Material
201	D1	1135	Unpainted Steel Column or Pile	499	K1	1508	High Mast Light Pole Foundations
202	F1	1423	Painted Steel Column or Pile	540	L1	1569	Open Gearing
204	F2	19917	P/S Conc Column or Pile	541	L1	1411	Speed Reducers
205	F3	17670	Reinforced Conc Column or Pile	542	L1	1641	Shafts
206	F8	5613	Timber Column or Pile	543	L1	1448	Shaft Bearings and Shaft Couplings
207	F2	253	Hollow Core Pile	544	L2	1256	Brakes
210	F5	3185	Reinforced Conc Pier Wall	545	L3	1833	Emergency Drive and Back Up Power System
211	F5	0	Other Material Pier Wall	546	L3	1430	Span Drive Motors
215	F5	34925	Reinforced Conc Abutment	547	L4	1042	Hydraulic Power Units
216	F8	3571	Timber Abutment	548	L5	1101	Hydraulic Piping System
217	F5	241	Other Material Abutment	549	L4	595	Hydraulic Cylinders/Motors/Rotary Actuators
220	F7	4965	Pile Cap/Footing	550	L6	499	Hopkins Frame
230	D1	77	Unpainted Steel Cap	560	L7	1527	Span Locks/Toe Locks/Heel Stops/Tail Locks
231	F1	735	Painted Steel Cap	561	L8	1684	Live Load Shoes/Strike Plates/Buffer Cylinders
233	F2	139	P/S Conc Cap	562	L6	2144	Counterweight Support
234	F6	29430	Reinforced Conc Cap	563	L6	2605	Access Ladder & Platforms
235	F8	3643	Timber Cap	564	L9	2477	Counterweight
240	G2	626	Metal Culvert	565	L9	1640	Trunnion/Straight and Curved Track
241	G1	6124	Reinforced Concrete Culvert	570	M1	1569	Transformers & Thyristors
242	G2	0	Timber Culvert	571	M2	1650	Submarine Cable
243	G2	19	Other Culvert	572	L5	2551	Conduit & Junction Boxes
290	H1	45560	Channel	573	M1	1355	Programmable Logic Controllers
298	I1	4410	Pile Jacket without Cathodic Protection	574	M3	1991	Control Console
299	I2	527	Pile Jacket with Cathodic Protection	580	M4	3244	Navigational Light System
300	B1	1992	Strip Seal Expansion Joint	581	M5	2092	Operator Facilities
301	B2	20091	Pourable Joint Seal	582	M6	367	Lift Bridge Specific Equipment
302	B3	7391	Compression Joint Seal	583	M6	126	Swing Bridge Specific Equipment
303	B4	1170	Assembly Joint/Seal (modular)	590	M7	642	Resistance Barriers
304	B5	2738	Open Expansion Joint	591	M7	1809	Warning Gates
310	E1	21533	Elastomeric Bearing	592	M8	2148	Traffic Signal
311	E2	6907	Moveable Bearing (roller, sliding, etc.)				

4.4 Onset of Deterioration

A problem noted in previous Florida research, as well as research by California (Thompson and Johnson 2005) and by the National Cooperative Highway Research Program (Patidar et al. 2007), is that the Markovian models used in Pontis have fairly rapid initial deterioration. This creates a serious problem for multi-year programming models, because it is difficult to configure such models to maintain a realistically high network condition level. Bridge engineers have long believed that transition probabilities are time-dependent, that the probability of transition is low for a new element, and increases with age.

A model using a Weibull curve has been proposed as an alternative that could ameliorate this problem (Agrawal & Kawaguchi 2009). Weibull distributions are very common in survival functions for reliability theory, where they are often used to model the probability of failure. However, they are useful for any change in state. Such a model is easily made age-based.

The Agrawal study in New York State used a Weibull model with a long time series of condition ratings in the style used in the National Bridge Inventory. In this type of rating system, unlike the CoRe Element system, the inspector rates the entire element using a single number, rather than dividing the total quantity of the element among condition states. In New York, each element receives a rating on a scale of 1 to 7. With a long time series of data, it is possible to determine the duration of an element in each condition state, so all state transitions can be quantified using age-based models.

With Pontis inspection data, a given unit of an element is not followed from one inspection to the next, so it is not possible to know the duration in most condition states. The age of the bridge does at least provide the duration in state 1, if no previous maintenance action has been taken. Therefore the solution investigated here is to use a survival function to model the probability of remaining in condition state 1, as a function of age. Subsequent transitions below state 2 would still be modeled using the Markovian models developed in the preceding section.

A Markovian model has a constant probability of transitioning from state 1 to state 2, so the survival function is used as an enhancement, to make the transition probability variable. A new bridge will have a very high probability, approaching 1.0, of remaining in state 1 from year to year. As the bridge ages, the probability decreases. Once a portion of an element deteriorates to condition state 2, Markovian deterioration takes over for the remainder of the process.

The Weibull curve has the following functional form:

$$y_{1g} = \exp\left(-(g/\alpha)^{\beta}\right) \tag{4.21}$$

where y_{1g} is the state probability of condition state 1 at age (year) g, if no intervening maintenance action is taken between year 0 and year g; β is the shaping parameter, which determines the initial slowing effect on deterioration; and α is the scaling parameter, calculated as:

$$\alpha = \frac{t}{ln(2)^{1/\beta}} \tag{4.22}$$

where t is the median transition time from state 1 to state 2, from the Markov model as calculated in equation 4.5.

Figure 4.3 shows the form of the Weibull curve, for four different values of the shaping parameter β, with t=20. A shaping parameter of 1 is mathematically equivalent to a Markov model, featuring the problematic rapid onset of deterioration. A shaping parameter of 2 introduces a delay, and higher values postpone significant deterioration even longer.

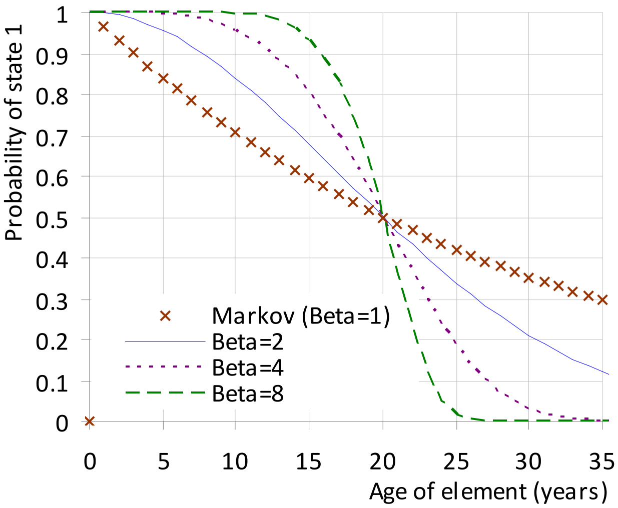


Figure 4.3. Comparison of shaping parameters

Note that all the curves in Figure 4.1 intersect in 20 years at a probability of 0.5, since the Markovian transition time is the same in all cases.

The Weibull curve can also be used in reverse, to calculate an equivalent age if the fraction in condition state 1 is known. This is useful if earlier preservation work has been done on the bridge, such that it behaves as though younger than its actual age. To calculate equivalent age:

$$\acute{g} = \alpha \times 10\hat{}\left(\frac{log\left(-ln(y_1)\right)}{\beta}\right) \qquad (4.23)$$

Then the forecast percent in state 1 in the following inspection is computed using Equation 4.21 with *g*=*g'*+2.This type of Markovian model refinement is not described in the literature, so the researcher investigated several methods to estimate the shaping parameter of the Weibull model.

4.4.1 Age-based vs. condition-based

An issue that complicates the estimation of any age-based model is the need for a long time series of historical data. Moreover, it is necessary that the bridges contributing to the analysis experience no preservation activity during the time period that is analyzed, in order to have a valid deterioration model. Two ways of minimizing or working around this issue are:

- Age-based models. A bridge that is sufficiently new, for example 10 years old, may be assumed to have had no maintenance work prior to the inspection being analyzed. In this case, it may be valid to use the age of the bridge as the duration of condition state 1, without necessarily having a chain of inspections or a complete maintenance activity record to prove that the bridge has never been in any other state.
- Condition-based models. In a pair of inspections, such as the data set used in the previous section, the first inspection might be interpreted as an indicator of equivalent age, regardless of any previous changes in condition or maintenance activities. Equation 4.23 can be used to convert the fraction in condition state 1 into this equivalent age. A predicted condition in the second inspection of the pair can then be forecast using equation 4.21 with an assumed age that is two years later than the first inspection.

The age-based model is simpler and more direct, but is limited by the length of the period during which it is safe to assume no action is taken on a new bridge. From the analysis of activity data conducted in

Section 2.1 above, it appears that once a bridge passes 20 years of age, preservation activity becomes very likely. For certain short-lived elements, such as expansion joints, even 20 years may be too long.

After experimentation with a number of alternative ways of limiting the duration of the age-based model, it was decided to limit the age range of historical data to 1.2 times the median transition time from state 1 to state 2, with a maximum of 20 years. A wide variety of scenarios were graphed and analyzed to develop these criteria. Both longer and shorter age ranges tended to increase the risk that the model would be biased by outliers or by maintenance activity.

In contrast to the age-based model, the condition-based model can use data from any age of structure, provided that no preservation activity is conducted between the first and second inspections of each pair. Since the data set of inspection pairs used in the deterioration model already satisfy this criterion to the greatest extent possible (as discussed in Section 2.2), it is logical to use the same data set for estimation of the shaping parameter.

In the estimation process, the Weibull model to be developed is still based on age, even though condition is used as a proxy for age. The equivalent age and the final predicted fraction in state 1, are both dependent on the unknown shaping parameter. This is taken into account as described in Section 4.3 below.

When the condition-based approach was used, it was applied as a supplement to the age-based approach, enabling the generation of additional data points over the full age range relevant to each model. Figure 4.4 compares the two approaches, using the clustered model described in the next section, for the example of reinforced concrete walls.

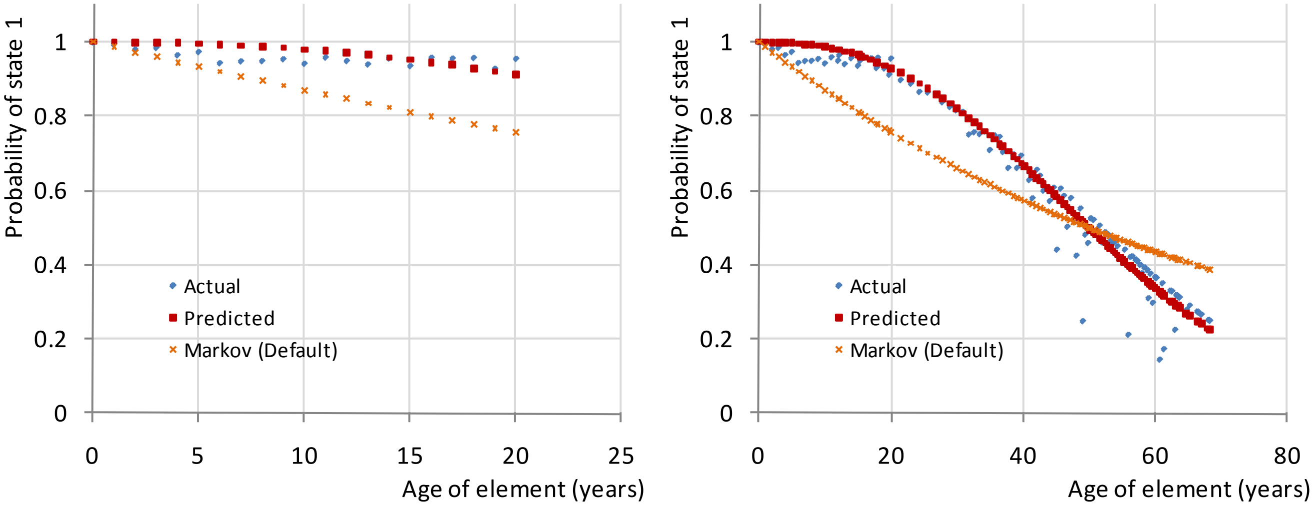


Figure 4.4. Comparison of Age-based (left) and Condition-based approaches

The graph on the left is a purely age-based model, limited to the first 20 years of a bridge's life due to the need to have a time series without maintenance activity. It is clear from the graph that deterioration in those initial years is much slower than the Markovian model would predict. Yet, only a small fraction of the element's life is used in the model.

On the right is a similar graph using the condition-based approach. It is able to use data points from bridges of any age, so it can fill out a more complete graph of the element's life. While the age-based approach has a sample size of 8,346, the condition-based approach can use 14,386 inspection pairs. It is interesting to note, however, that the two models produced very similar results: the shaping parameter was 2.2 in the age-based approach and 2.4 in the condition-based approach. This was true for most of the models analyzed. The reason for the similarity is that both models are constrained to the Markovian median transition time, so the probability of state 1 must cross the 50% line in the same year in both cases.

4.4.2 Sampling vs. clustering

Another distinction arises when determining the unit of analysis of the input data points in model estimation. The most obvious approach is to use bridge inspection pairs as the basic unit of input. However, this raises some difficulties:

- The iterative estimation procedure (described in the next section) is limited in the number of data points it can handle. In many cases there are more data points available than can be used.
- Certain elements are inspected on an "each" basis, with the entire quantity placed in only one condition state. In Florida, this includes decks and channels. For these elements, the fraction in condition state 1 is either 1 or 0, with nothing in between.
- Graphical analysis was very useful in visualizing and evaluating the models. But data points used in these models tend to concentrate in specific areas, making it difficult to visualize the actual distribution of data.

The first point is readily handled using random sampling, but the other points are not. An alternative approach is to create clusters of inspection pairs, based on actual age (for the age-based model) or equivalent age (for the condition-based model). The fraction in state 1 is computed as an average over all inspections in the cluster, so even bridge decks can be expressed with non-integer values.

To avoid creating a new dependency on the unknown shaping parameter, the equivalent ages of clusters in the condition-based model are computed using a shaping parameter of 1.0. This means the equivalent age values are not integers and are not evenly spaced in time. However, this doesn't bias the model results.

For condition-based sampled models, the model generation algorithm attempted to select an equal number of age-based and condition-based data points when possible, with the total not to exceed 32,000 inspection pairs. This limitation helped the Excel-based solution procedure to work efficiently. For condition-based clustered models, the age-based portion of the data set had one data point for each year of age. The condition-based portion had a number of data points equal to the duration of the model, which ranged from 30 to 100 years depending on the longevity of the elements being modeled.

Figure 4.5 compares the sampled and clustered approaches, again for reinforced concrete walls. In the sampled version at left, the graph is difficult to read, because the main distinction from year to year is the degree of concentration of data points at the perfect 1.0 level of probability in state 1. The clustered model at right shows the average probability for each year, providing much more clarity. The two models are nearly identical in their shaping parameters: 2.2 in both cases.

Figure 4.6 shows a more pronounced example for concrete bridge decks. Since decks are inspected as "each," all the data points in the sampled model on the left are at 1.0 or 0.0 on the vertical axis. However, the distribution of points between the two levels changes over time, yielding a meaningful model even though it is difficult to see on the graph. The clustered model at right shows the average condition over the whole set of bridge decks each year, making the fit of the model more obvious. Again both models produced nearly the same value of the shaping parameter, 1.4 in both cases.

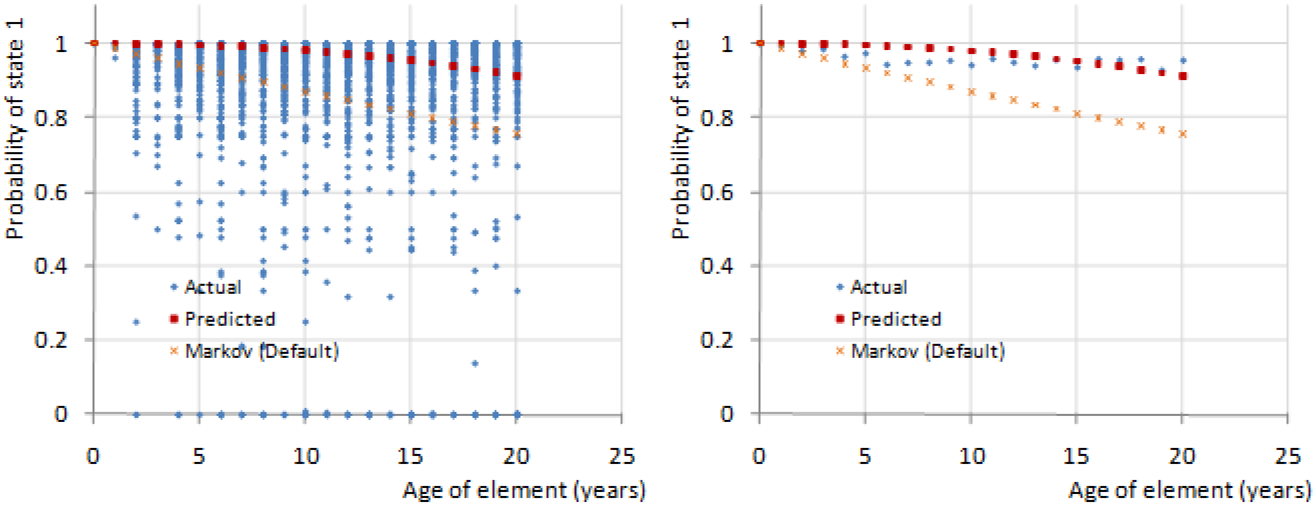


Figure 4.5. Comparison of sampled (left) and clustered approaches

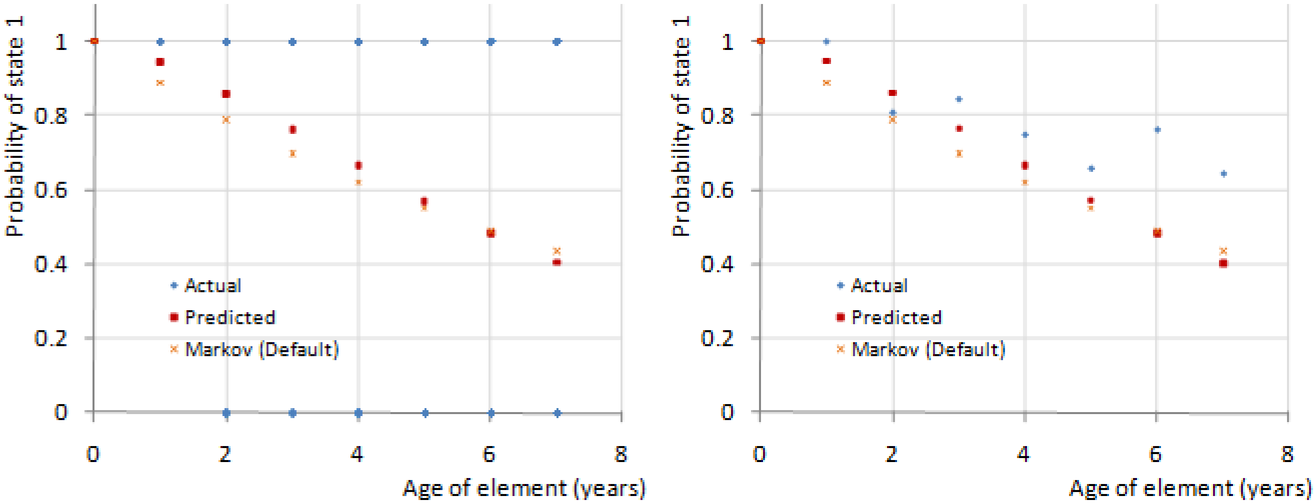


Figure 4.6. Comparison of sampled (left) and clustered, for concrete bridge decks

4.4.3 Model estimation

Weibull models were estimated for each element category, element material, element type, and element, to determine the best level of analysis for reporting and using the results. Environmental categories were combined in all the models. A total of 1060 models were developed using the four combinations of approaches described above.

The functional form of the Weibull model is too complex for ordinary regression or any closed-form solution. So the shaping parameters were estimated using an iterative maximum likelihood procedure implemented using Excel's Solver module. An Excel table (Table 4.17) was generated with columns for x_{1g} (fraction in condition state 1 in the first inspection of the pair, for condition-based data points), age (either NBI age for age-based data, or the calculated equivalent age from Equation 4.23, implemented as a worksheet formula), actual $y_{1(g+2)}$ (fraction in condition state 1 in the second inspection of each pair), and predicted fraction in state 1 (Equation 4.21, implemented as a worksheet formula). The scaling parameter was calculated using Equation 4.22 from the corresponding results of the one-step Markovian model for the transition from state 1 to state 2.

Table 4.17. Example Excel table used in estimation of the Weibull model

Condition-based clustered model
Element type J2- Reinforced concrete wall (4 states) (Sample=14385)

Inspection pair			Prediction		Evaluation	
Actual X1	Actual or equiv. age	Actual Y1	Predicted Y1	Markov Y1	SS_t	SS_e
	0.0000	1.0000	1.0000	1.0000	0.0000	0.0000
	1.0000	0.9940	1.0000	0.9862	0.0001	0.0000
	2.0000	0.9804	0.9997	0.9726	0.0001	0.0004
	3.0000	0.9849	0.9993	0.9592	0.0007	0.0002
	4.0000	0.9655	0.9986	0.9459	0.0004	0.0011
	5.0000	0.9739	0.9975	0.9329	0.0017	0.0006
	6.0000	0.9443	0.9961	0.9200	0.0006	0.0027
	7.0000	0.9493	0.9944	0.9073	0.0018	0.0020
	8.0000	0.9499	0.9922	0.8948	0.0030	0.0018
	9.0000	0.9550	0.9896	0.8824	0.0053	0.0012
	10.0000	0.9428	0.9866	0.8703	0.0053	0.0019
	11.0000	0.9594	0.9831	0.8583	0.0102	0.0006
	12.0000	0.9502	0.9791	0.8464	0.0108	0.0008
0.9860	12.1574	0.9646	0.9784	0.8446	0.0144	0.0002
	13.0000	0.9410	0.9746	0.8347	0.0113	0.0011
	14.0000	0.9571	0.9696	0.8232	0.0179	0.0002
	15.0000	0.9366	0.9641	0.8119	0.0156	0.0008
0.9730	15.3415	0.9496	0.9622	0.8080	0.0200	0.0002
	16.0000	0.9589	0.9581	0.8007	0.0250	0.0000
	17.0000	0.9567	0.9516	0.7896	0.0279	0.0000
0.9593	17.8178	0.9306	0.9459	0.7807	0.0225	0.0002
	18.0000	0.9583	0.9445	0.7787	0.0323	0.0002
	19.0000	0.9295	0.9369	0.7680	0.0261	0.0001
0.9465	19.7318	0.9125	0.9310	0.7602	0.0232	0.0003
	20.0000	0.9559	0.9288	0.7574	0.0394	0.0007
0.9332	21.4628	0.8981	0.9159	0.7421	0.0243	0.0003
0.9201	23.0069	0.8885	0.9011	0.7264	0.0263	0.0002
0.9082	24.2824	0.8664	0.8880	0.7136	0.0233	0.0005
0.8956	25.5544	0.8647	0.8740	0.7011	0.0268	0.0001
0.8823	26.8043	0.8592	0.8595	0.6891	0.0290	0.0000
0.8717	27.7585	0.8384	0.8480	0.6800	0.0251	0.0001
0.8584	28.9038	0.8257	0.8336	0.6692	0.0245	0.0001
0.8470	29.8405	0.8169	0.8213	0.6606	0.0244	0.0000
0.8345	30.8269	0.8126	0.8080	0.6516	0.0259	0.0000

A column was included to show the default prediction of the fraction in state 1, if a shaping parameter of 1.0 is used. This is equivalent to the Markovian model without the Weibull refinement. To measure model performance, a variation on the r^2 statistic was prepared, using Equation 4.6 but with $\bar{y}$ equal to the default (Markovian) prediction of the fraction in state 1. So r^2 became a measure of additional explanatory power beyond what was already provided by the Markov model.

The Solver was configured to generate alternative shaping parameter values in the range from 1.0 to 8.0, and evaluate the goodness-of-fit using a log likelihood function based on the normal distribution. The parameter value giving the highest log likelihood was selected.

4.4.4 Results

As was the case for the deterioration model, the data set did not have a sufficient number of inspections to estimate models for most of the elements individually. Yet, the element category and material levels of analysis were not detailed enough to provide useful distinctions among elements. So the element type model, using the definitions in Table 4.16, produced the best balance of detail and completeness.

It was found on examination of the results that all four combinations of age-based vs. condition-based and sampled vs. clustered produced very similar values of the shaping parameter. The main exception was in four cases in the condition-based clustered model where some numerical instability was found, evidenced by a local optimum of the shaping parameter that prevented the algorithm from finding a global optimum in those cases. The sample sizes were mostly generous and there wasn't a strong statistical reason to prefer one approach over another. In the end it was decided to use the results from the age-based sampled model, because it was the simplest.

An observation that was apparent in the results was that element types fell into natural groups. For example, all of the coated steel types had similar values of the shaping parameter and good reasons to believe that the onset of deterioration would work in a similar way for all of them. As a result, the element types were further summarized into groups in order to report the final results for the Weibull model in Table 4.18.

Table 4.18. Final Weibull model shaping parameters

Group name	Wt.Avg Beta	Sample	Wt.Avg r-sq
Concrete deck/slab	1.3	2119	0.01
Approach slab	1.0	7878	0.00
Simple expansion joint	1.0	4310	0.00
Complex expansion joint	1.4	1114	0.01
Uncoated steel	1.1	1039	0.00
Coated steel	1.8	2968	0.05
Portland cement concrete	2.0	54935	0.23
Timber above ground	1.9	1796	0.11
Timber in ground	3.5	7789	0.32
Other material (asphalt, masonry)	2.5	8746	0.33
Bearing	1.9	9395	0.23
Channel	1.0	6021	0.00
Earth wall	1.6	2771	0.14
Sign structures and poles	1.0	8019	0.00
Moveable bridge mechanical	1.6	1652	0.04
Moveable bridge structure	4.1	548	0.37
Moveable bridge electrical	3.0	1272	0.23
Moveable bridge other	1.1	457	0.00
Smart flags	1.2	229	0.00

The models for decks, expansion joints, unpainted steel, and channels were weakest, adding little to the explanatory power of the Markovian model. This is seen in the low r^2 values in Table 4.18 and shaping parameter values close to 1.0. Other elements, however, had stronger models where the shaping parameter significantly improved the deterioration forecasts.

Table 4.19 at the end of this section reports the final analysis results for both the Markovian model and the shaping parameter. The final models completely cover all elements in Florida's Pontis inventory with a sufficient degree of statistical confidence. Figure 4.7 presents a series of comparisons among element type models, using the new Markovian model and shaping parameters. The shapes of the curves and relationships among element types are largely intuitive.

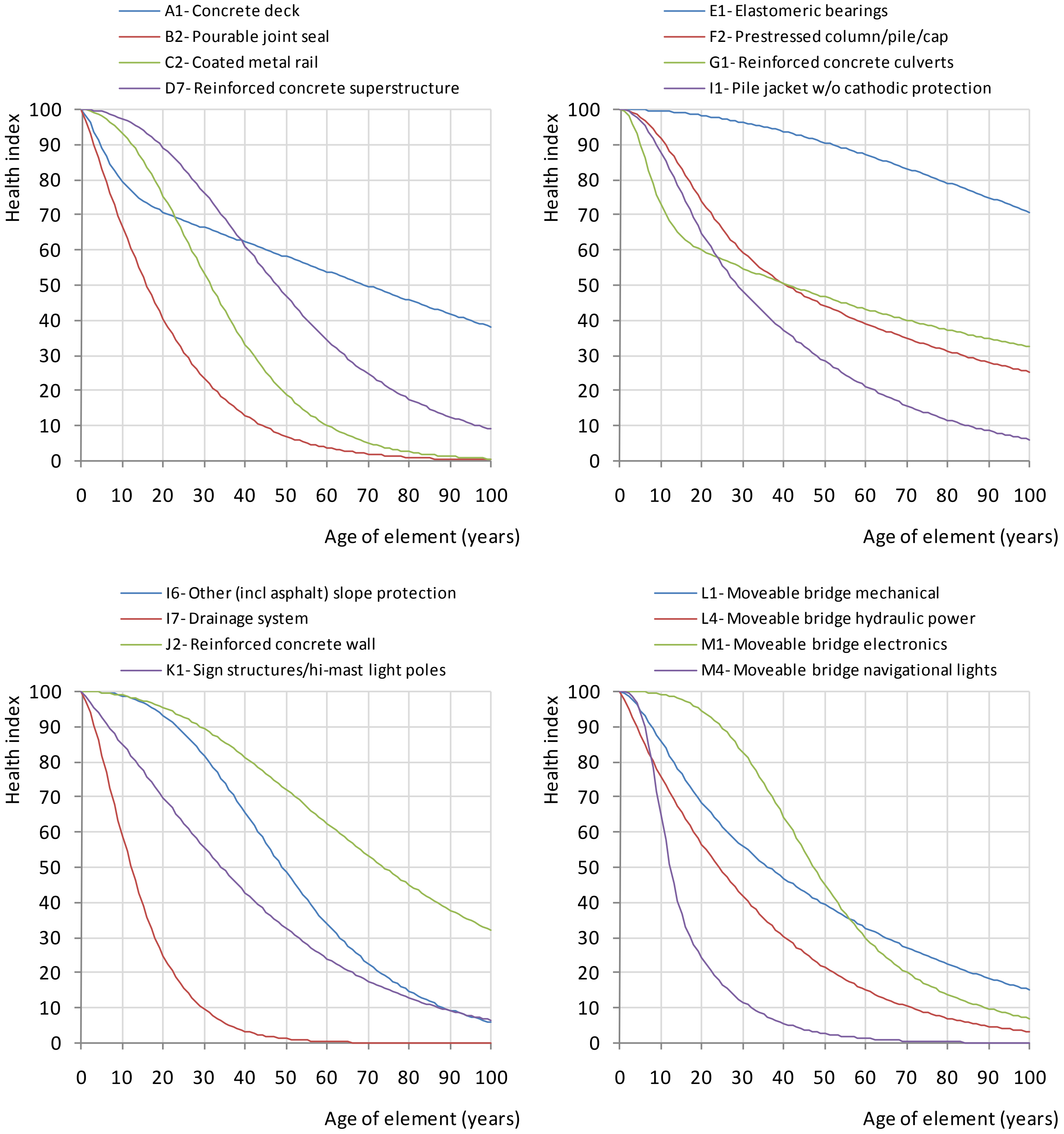


Figure 4.7. Comparisons of deterioration models among element types

Most of the final models appear able to stand on their own based on the statistical analysis. However, a few have unusual characteristics that may require expert review and adjustment. In Table 4.19, it can be seen that element type D6, prestressed concrete superstructures, has a very long holding time in condition state 1, requiring a median of 292.9 years to move to state 2. Even though this is an accurate computation based on a large sample of 15,627 element inspections, the transition time appears unreasonably high. Figure 4.8 shows how it compares with other superstructure materials.

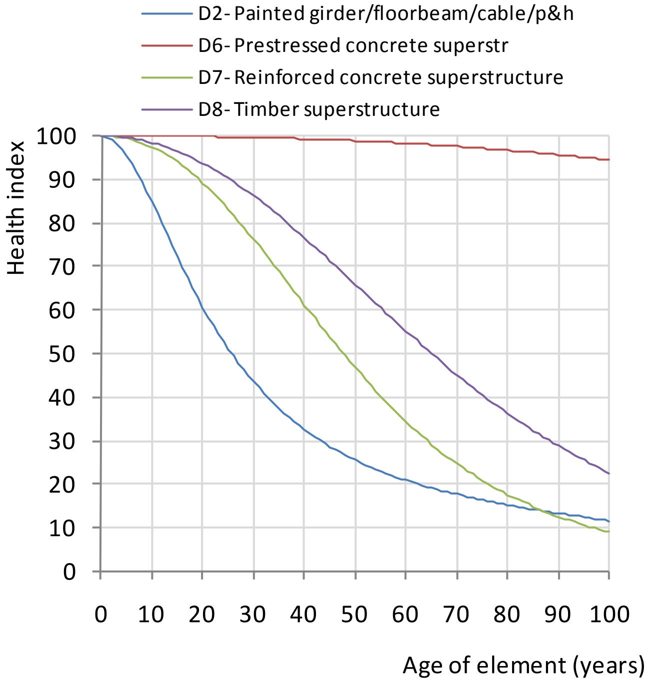


Figure 4.8. Comparison of superstructure materials

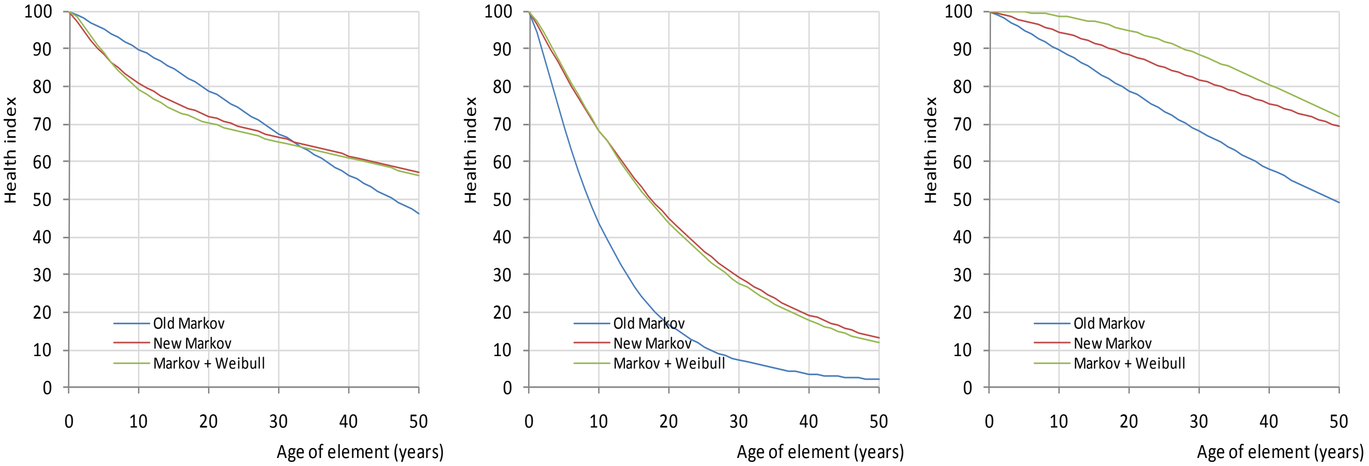
Figure 4.9 on the next page presents more comparisons, this time for groups of element models. To compute these graphs, the actual element quantities and replacement costs in the Florida inventory were used in order to develop reasonable element weights for use in Equation 4.3 to compute the health index. The environment factors in Table 4.14 were also used to accurately reflect the differing deterioration rates.

Three versions of the deterioration model were computed separately and then compared on each graph, to show how the new models differ from the old ones. The first (blue) line uses the results of the expert judgment elicitation conducted with FDOT staff in 2001. The second (orange) line uses the new Markov models as developed in section 4.3 of this report. The third (green) line also uses the new Markov models, but combines them with the Weibull shaping parameters developed earlier in this section.

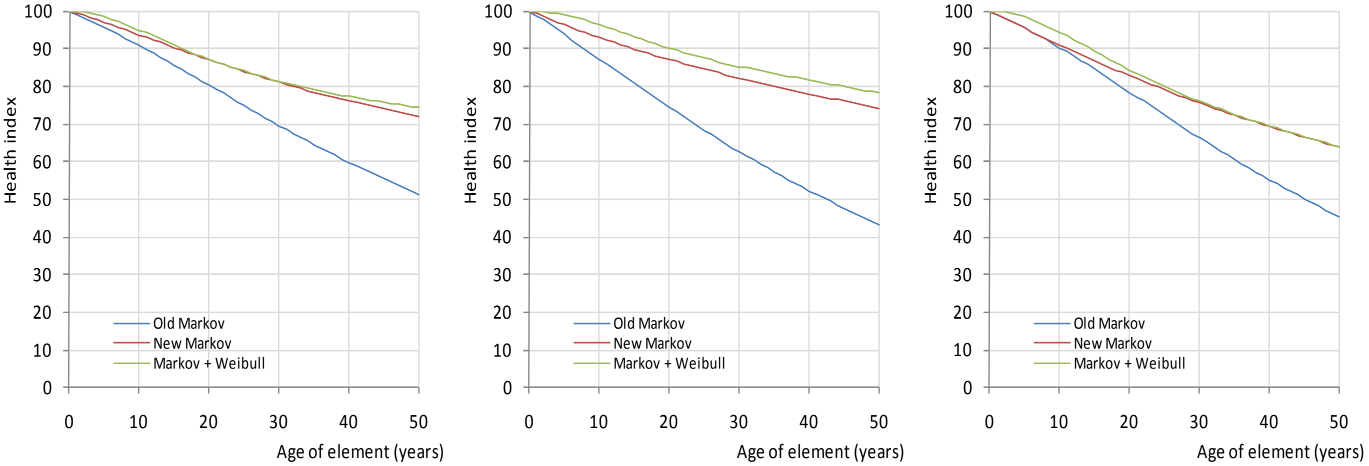
In Figure 4.9, a common pattern can be seen, where the new Markovian models are considerably slower than the old models. The Weibull shaping parameter in many cases further slows deterioration in the early years of the element's life. This is exactly the type of outcome that was expected.

But certain elements stand out as different from the pattern: decks and slabs, and culverts. In both cases, the new curves are concave upward because of very fast deterioration from state 1 to state 2. These counter-intuitive patterns are consistent across all elements in these groups, and for both estimation methods (regression and one-step). It is not clear why these elements are so much different from the others.

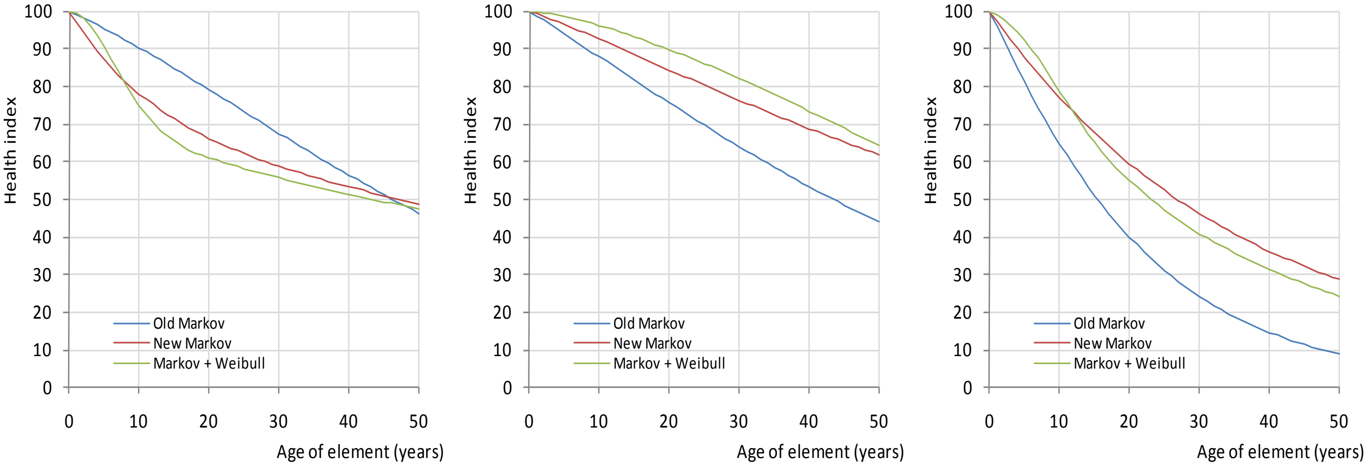
Because the elements are important in health index computations, the effect of the unexpected behavior is to nearly negate the analytical benefit of slowing the initial rate of deterioration. As a result, a careful expert review is recommended.



Decks and slabs Expansion joints Railings



Superstructures Bearings Substructures



Culverts Other elements Moveable bridge elements

Figure 4.9. Comparison of the old and new model results

Table 4.19. Final deterioration model parameters

			Median transition times (from-to states, in years)						
Element type	States	Elemts	1-2	2-3	3-4	4-5	1-5	Count (r^2)	Beta
A1- Concrete deck	5	3	5.8	47.1	35.9	23.4	146	19064 (0.72)	1.3
A2- Concrete slab	5	2	4.3	44.6	13.9	15.0	98	6852 (0.66)	1.3
A3- Prestressed concrete slab	5	1	5.2	72.3	21.3	39.3	174	4785 (0.71)	1.3
A4- Steel deck	5	3	3.4	1.8	11.3	10.9	37	3990 (0.50)	1.1
A5- Timber deck/slab	4	4	5.1	11.7	14.7	0.0	41	2739 (0.60)	1.9
A6- Approach slabs	4	2	11.6	25.0	27.9	0.0	83	38434 (0.71)	1.0
B1- Strip Seal expansion joint	3	1	12.8	45.4	0.0	0.0	67	1992 (0.62)	1.0
B2- Pourable joint seal	3	1	9.9	8.3	0.0	0.0	23	20091 (0.76)	1.0
B3- Compression joint seal	3	1	6.2	10.7	0.0	0.0	21	7391 (0.68)	1.4
B4- Assembly joint/seal	3	1	13.9	13.7	0.0	0.0	34	1170 (0.65)	1.4
B5- Open expansion joint	3	1	18.1	30.1	0.0	0.0	58	2738 (0.70)	1.4
B6- Other expansion joint	3	1	19.2	60.4	0.0	0.0	92	757 (0.75)	1.4
C1- Uncoated metal rail	4	1	73.7	5.2	0.4	0.0	84	1453 (0.61)	1.1
C2- Coated metal rail	5	1	17.7	9.5	4.5	2.4	45	5075 (0.69)	1.8
C3- Reinforced concrete railing	4	1	67.6	24.1	37.7	0.0	163	24827 (0.72)	2.0
C4- Timber railing	3	1	12.3	8.7	0.0	0.0	26	889 (0.71)	1.9
C5- Other railing	3	1	36.7	15.8	0.0	0.0	62	11238 (0.73)	2.5
D1- Unpainted steel super/substructure	4	11	12.7	8.7	13.3	0.0	46	1349 (0.82)	1.1
D2- Painted girder/floorbeam/cable/p&h	5	5	10.5	7.6	7.8	56.9	99	7273 (0.76)	1.8
D3- Painted steel stringer	5	1	10.0	17.0	4.7	274.6	323	1991 (0.79)	1.8
D4- Painted steel truss bottom	5	2	13.0	4.6	13.3	6.6	51	762 (0.80)	1.8
D5- Painted steel truss/arch top	5	2	7.1	5.2	11.3	151.8	189	761 (0.84)	1.8
D6- Prestressed concrete superstr	4	4	292.9	13.2	14.3	0.0	335	15627 (0.82)	2.0
D7- Reinforced concrete superstructure	4	5	32.4	9.3	21.3	0.0	80	1854 (0.79)	2.0
D8- Timber superstructure	4	4	41.4	26.9	5.8	0.0	92	2682 (0.79)	1.9
E1- Elastomeric bearings	3	1	95.8	242.2	0.0	0.0	393	21533 (0.80)	1.9
E2- Metal bearings	3	5	14.0	48.4	0.0	0.0	72	14730 (0.70)	1.9
F1- Painted steel substructure	5	2	8.4	7.4	2.4	4.9	32	2158 (0.75)	1.8
F2- Prestressed column/pile/cap	4	3	16.1	24.4	77.2	0.0	142	20309 (0.75)	2.0
F3- Reinforced concrete column/pile	4	1	40.6	9.8	120.1	0.0	200	17670 (0.84)	2.0
F5- Reinforced concrete abutment	4	4	86.9	15.1	496.4	0.0	656	38351 (0.82)	2.0
F6- Reinforced concrete cap	4	1	144.9	8.6	198.6	0.0	428	29430 (0.83)	2.0
F7- Pile cap/footing	4	1	9.2	14.0	78.6	0.0	116	4965 (0.69)	2.0
F8- Timber substructure	4	3	23.7	17.7	4.6	0.0	58	12827 (0.79)	3.5
G1- Reinforced concrete culverts	4	1	7.0	37.2	137.7	0.0	208	6124 (0.72)	2.0
G2- Metal and other culverts	4	3	8.5	29.2	34.4	0.0	91	645 (0.75)	1.1
H1- Channel	4	1	9.0	16.6	25.6	0.0	66	45560 (0.68)	1.0
I1- Pile jacket w/o cathodic protection	4	1	13.2	17.1	17.7	0.0	63	4410 (0.79)	2.0
I2- Pile jacket with cathodic protection	4	1	19.2	56.0	43.3	0.0	150	527 (0.74)	2.0
I3- Fender/dolphin/bulkhead/seawall	4	6	11.0	9.4	27.2	0.0	60	3420 (0.80)	2.0
I4- Reinforced conc slope protection	4	1	56.4	11.7	14.6	0.0	99	9936 (0.73)	2.0
I5- Timber slope protection	4	1	62.1	17.3	136.1	0.0	260	2755 (0.81)	3.5
I6- Other (incl asphalt) slope protection	4	1	34.8	13.2	9.3	0.0	71	16353 (0.78)	2.5
I7- Drainage system	4	1	7.7	2.3	2.6	0.0	17	1480 (0.64)	1.1
I7- Drainage system (coated)	5	1	6.5	3.1	0.9	1.7	17	497 (0.61)	1.1
J1- Uncoated metal wall	4	1	9.2	5.9	70.8	0.0	95	792 (0.73)	1.1
J2- Reinforced concrete wall	4	1	49.9	11.2	66.1	0.0	158	30918 (0.76)	2.0
J3- Timber wall	4	1	24.3	8.9	14.0	0.0	61	3325 (0.81)	3.5
J4- Other (incl masonry) wall	4	1	10.1	18.2	18.9	0.0	62	951 (0.66)	2.5
J5- Mechanically stabilized earth wall	4	1	75.8	9.6	17.4	0.0	119	2995 (0.54)	1.6
K1- Sign structures/hi-mast light poles	4	4	14.6	18.3	6.6	0.0	51	14368 (0.54)	1.0
K1- Sign str/hi-mast light poles (coated)	5	4	10.5	7.6	7.8	56.9	99	7273 (0.76)	1.0

Table 4.19. Final deterioration model parameters (continued).

			Median transition times (from-to states, in years)						
Element type	States	Elemts	1-2	2-3	3-4	4-5	1-5	Count (r^2)	Beta
L1- Moveable bridge mechanical	4	4	12.2	34.2	12.2	0.0	73	6069 (0.74)	1.6
L2- Moveable bridge brakes	4	1	5.4	7.4	5.8	0.0	25	1256 (0.67)	1.1
L3- Moveable bridge motors	4	2	9.3	6.8	9.6	0.0	34	3263 (0.49)	1.6
L4- Moveable bridge hydraulic power	4	2	7.9	15.1	13.3	0.0	48	1637 (0.65)	1.1
L5- Moveable bridge pipe and conduit	3	2	5.6	27.5	0.0	0.0	37	3652 (0.54)	1.6
L6- Moveable bridge structure	5	3	10.3	4.4	1.8	11.3	38	5248 (0.64)	4.1
L7- Moveable bridge locks	4	1	3.5	5.6	15.3	0.0	31	1527 (0.64)	1.1
L8- Moveable bridge live load items	3	1	5.6	22.4	0.0	0.0	32	1684 (0.65)	1.6
L9- Moveable bridge cw/trunion/track	4	2	13.0	13.6	81.0	0.0	124	4117 (0.70)	1.6
M1- Moveable bridge electronics	3	2	38.2	20.2	0.0	0.0	70	2924 (0.53)	3.0
M2- Moveable bridge submarine cable	3	1	10.2	7.0	0.0	0.0	22	1650 (0.53)	3.0
M3- Moveable bridge control console	3	1	9.1	16.6	0.0	0.0	31	1991 (0.64)	3.0
M4- Moveable bridge navigational lights	3	1	9.0	9.5	0.0	0.0	23	3244 (0.56)	3.0
M5- Moveable bridge operator facilities	3	1	13.5	37.1	0.0	0.0	59	2092 (0.51)	1.1
M6- Moveable bridge misc equipment	3	2	0.9	10.3	0.0	0.0	13	493 (0.24)	1.1
M7- Moveable bridge barriers/gates	3	2	10.2	19.8	0.0	0.0	37	2451 (0.70)	1.6
M8- Moveable bridge traffic signals	3	1	30.0	6.3	0.0	0.0	41	2148 (0.59)	3.0
S1- Smart flag	3	4	15.2	5.9	0.0	0.0	25	1510 (0.59)	1.2
S1- Smart flag	4	5	7.5	10.6	14.2	0.0	43	1462 (0.67)	1.2
S1- Smart flag	5	1	2.4	0.6	4.1	16.2	29	142 (0.53)	1.2

States = number of condition states in the element definitions
Elmts = number of elements belonging to the element type
Median transition time from state 1 to state 5 is the decay life
Beta = Weibull model shaping parameter

4.5 Action Effectiveness Model

In Pontis, transition probability matrices are used as a general method of predicting future conditions, whether or not the agency performs a preservation action on the structure. The case where no action is taken, often known as the "do-nothing" case, was handled in sections 4.3 and 4.4 as the deterioration model. What remains is to develop the transition probabilities for the "do-something" case, the action effectiveness model.

Do-something transition probabilities are used in the same way as do-nothing. Generalizing from Equation 4.1,

$$y_k = \sum_j x_j \, p_{a(j)jk} \text{ for all } k \tag{4.24}$$

where x_j is the probability of being in condition state j at the beginning of the year; y_k is the probability of being in condition state k at the end of the year; and $p_{a(j)jk}$ is the transition probability from j to k, if action $a(j)$ is applied. The choice of action is dependent on state j: it may for example be repairs to state 3 and replacement of the portions in state 4, with do-nothing in states 1 and 2.

4.5.1 Data preparation

A variety of complications must be handled when using historical data to estimate do-something probabilities:

1. Many of the elements are rather uncommon (uncoated steel cables, for example), and so the actions defined for them will also be uncommon. The analysis conducted in section 4.3 for deterioration, showed that it was not possible to estimate an element-level deterioration model for most element/environment combinations, without aggregating them, due to insufficient sample size. But Table 4.5 showed that improvements in condition, indicative of possible actions, occur in only about 9% of inspection pairs. So amassing a sufficient sample size for preservation actions is much more difficult than for do-nothing.

2. It is common in the activity data to list multiple activities on the same bridge at the same time. Often such actions are classified in the same action sub-category, but not always. This means that the change in condition in any given inspection pair may result from multiple activities, and possibly multiple action sub-categories.
3. Bridge inspections are normally conducted on a two-year interval. So if an action is taken during the 2-year interval, there will be one year of do-something and one year of do-nothing. Unless the action effectiveness model adjusts for this, it will be systematically biased.
4. The activity records processed in section 4.2 don't indicate which elements were worked on, or which specific Pontis action was performed. While it is possible, as was done in section 4.2, to narrow the range of applicable actions, there is not a unique correspondence between activities and Pontis actions.
5. Each action $a(j)$ may yield conditions in any of the other condition states. If two or more actions were performed for different states j, then the effects of these actions will be mixed together in the snapshot of condition taken after the action. In particular, unless the do-something action(s) are applied to the entirety of an element, the effect of the action(s) will be mixed with the effect of do-nothing on states that were not acted upon. (Refer back to Figure 4.1 to see this schematically.)

The researcher investigated a number of alternative estimation methods that were more or less complex depending on how many assumptions were made regarding these complications. The objective is to make as few simplifying assumptions as possible, but still produce an algorithm that is feasible to solve, robust, and has sufficient statistical validity and sample size.

In order to respond effectively to complication #1, a clear requirement was to aggregate Pontis preservation actions into a smaller number of action sub-categories. The method for doing this was described in section 4.2. After investigating sample sizes based on the methodology described here, it was decided that the action effectiveness model would need to be estimated at the action sub-category level, distinguishing elements only when they have differing numbers of condition states in their definitions. This means the do-something transition probabilities do not vary by element, environment, or condition state, except to the extent that action subcategories are only associated with specific elements and condition states.

Some of the action sub-categories have effectiveness models that are determined by their definitions. For example, all element replacement sub-categories are defined as actions that replace all or part of an element with new parts and materials. Thus, by definition the actions restore 100% of the affected part of the element to condition state 1.

In contrast, activities in action category 400 are defined as having no effect on condition. They are regarded as routine maintenance and are not analyzed or programmed by Pontis. As Table 4.11 showed, these make up a large fraction (48%) of the activity data set. They are completely ignored in the action effectiveness analysis.

To deal with complication #2 and to simplify the activity dataset, activities were filtered to remove any that did not have clear completion dates and action sub-category results from section 4.2. If any two or more records had the same bridge ID, action sub-category, and completion date, these were combined. Records with action sub-category 400 and above were removed. Element inspection data were also cleaned to remove any having zero quantities or other invalid data, and to combine element inspections if they occurred on the same date and element, but with different structure units or environments.

To begin handling complications #3 and #4, each activity record was matched with element inspections in the most recent inspection before it, and the next inspection after it. Each element inspection record in the inspection immediately before the activity was examined for condition states having non-zero quantities. Each condition state of each element has a set of MR&R action definitions in Pontis, each of which has a corresponding action sub-category. If one of these action sub-categories matched the activity, then the element inspection was used. It was required that there also be a matching element inspection immediately after the activity, and that the condition improve (according to Equation 4.4) from before the activity to after for that element. Activities were rejected if suitable before- and after- element inspections could not be found.

This filtering partially addresses complication #3 by taking advantage of the fact that certain bridges are inspected on one-year or even shorter intervals. In the filtered data set, 36% of the activities have these shorter inspection intervals surrounding them. It partially addresses complication #4 by accepting for each activity only the elements, and their feasible corresponding action sub-categories, where an improvement in condition was found. This narrows the range of possible elements and actions which may have been performed.

4.5.2 Model estimation

Because of complication #5, it was necessary to find a way to isolate the effect of each action sub-category from other do-something actions. A regression approach similar to the ones in sections 4.3 and 4.4 was considered, but the problem formulation would have been very complex. There was no natural way to subdivide the problem into separate models, so all of the do-something transition probabilities for all the action sub-categories would have had to be estimated in the same grand model.

A simpler method was available because of the large sample sizes of inspections and activities available in the database. It was decided to simply eliminate any activity whose inspection interval (from the before-inspection to the after-inspection) contained any other activities of any other action sub-category for the same element. Thus, any change in condition could always be ascribed to just one action sub-category. Table 4.20 shows the sample sizes when action combinations are included, and when they are excluded. The difference was small.

Table 4.20. Sample sizes by action sub-category

Action sub-category		Action combinations	
		With	Without
201	Rehab deck/replace overlay	15	6
202	Rehab steel	112	68
203	Rehab concrete	286	237
204	Rehab timber	26	18
205	Rehab masonry	36	33
206	Rehab MSE	31	31
211	Rehab joint	58	45
213	Rehab bearing	45	40
221	Rehab slope protection	145	143
222	Rehab channel	372	154
223	Rehab drainage system	1	0
231	Rehab machinery	185	151
243	Rehab cable	0	0
246	Mudjacking	217	215
301	Repair deck and substrate	82	82
302	Spot paint	1296	932
303	Clean rebar and patch	2008	1974
311	Repair joint	216	198
331	Repair/lubricate machinery	421	306
	Total	5552	4633

Because of complication #3, it was necessary to find a way to correct for deterioration that occurs during the inspection interval containing the activity. If the "before" inspection was closer to the activity completion date than the "after" inspection, then the condition in the "before" inspection was deteriorated by one year, using the element's deterioration model as developed in section 4.4.

If the "after" inspection was closer to the activity completion date, then a method was needed to correct for the deterioration that occurred after completion of the action, but before the next inspection. The method that was developed is called an "un-deterioration model". The method uses Equation 4.1, but transforms it algebraically to work backward from the known y_k to unknown x_j. It also reverses the Weibull model, by first calculating the equivalent age in the "after" inspection, subtracting one year, and re-computing the probability of state 1. This is not an exact method, and required careful controls at each step to avoid probabilities that are less than zero or more than 1.0. But it proved to be a useful approximation that had the intended effect of correcting the bias that would otherwise occur.

After these corrections, the difference between the "before" and "after" inspections gave a good indication of the improvement that was achieved on the bridge element by the activity.

To calculate the do-something transition probabilities, a prediction equation was used, similar to Equation 4.9 but intended for the do-something case. This equation uses do-something probabilities of the same or improved condition, for each condition state where the action sub-category is feasible. It uses the deterioration model for condition states where the action is infeasible. For elements that are inspected as "each" (decks and channels), the do-something probabilities are applied to all states. The prediction equation is:

$$[Y] = [A][X] \tag{4.25}$$

This expands to:

$$\begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \end{bmatrix} = \begin{bmatrix} d_{11} & p_{12} & 0 & 0 \\ a_1 & d_{22} & p_{23} & 0 \\ a_1 & a_2 & d_{33} & p_{34} \\ a_1 & a_2 & a_3 & d_{44} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} \tag{4.26}$$

In this equation the rows of the transition probability matrix *[A]* differ depending on whether the activity's action sub-category is feasible in the corresponding condition state. If the action sub-category is feasible, then the elements of the matrix are as follows:

$d_{jk} = a_k$, the probability of being in state k after the action is taken
$p_{jk} = 0$, as no deterioration is modeled if an action is taken in state j

Note that the action effectiveness probabilities a_k only appear in rows representing condition states j where the action sub-category of the activity is feasible. For rows where the action sub-category is not feasible, the elements of the matrix are:

d_{jk} = the do-nothing probability of remaining in the same condition state (deterioration model)
P_{jk} = the do-nothing probability of deteriorating to the next condition state
$a_k = 0$, as no improvement in condition can happen to states where no action is taken

The do-nothing transition probabilities are already known from sections 4.3 and 4.4, so it is only necessary to solve algebraically for the do-something probabilities a_k. An algorithm was developed to do this individually for each activity, and normalize the results to ensure that each element is between 0 and 1 inclusive, and the sum of the *[A]* vector is 1.0. The results were finally averaged over all activities by action subcategory and number of condition states, to yield the action effectiveness model.

Table 4.21 shows the results of this analysis and compares it to the average do-something probabilities developed in 2001 from an expert elicitation process. It can be seen that the new models have significantly more effective actions, with the probability of condition state 1 much larger than the panel of experts had estimated. The main exceptions were rehabilitation of steel and concrete, which proved less effective than had been estimated earlier. (However, *repairs* of steel and concrete were much more effective.)

After all the necessary processing of maintenance records, the original data set of 93,615 activity records was reduced to 4,633 maintenance events (4.9%) that could be used in model estimation. A few of the models had sample sizes too low to trust, so in some cases it was decided to borrow models from other, similar, action sub-categories. Table 4.22 shows the final recommended models.

Table 4.21. Raw effectiveness model and comparison with expert elicitation

				New model - raw results					Old model				
Action sub-category		States	Sample	State1	State2	State3	State4	State5	State1	State2	State3	State4	State5
201	Rehab deck/replace overlay	4	6	43.88	56.12	0.00	0.00	0.00	35.57	61.03	3.41	0.00	0.00
201	Rehab deck/replace overlay	5	0						60.18	13.18	1.55	6.63	18.47
202	Rehab steel	4	21	41.03	1.85	56.44	0.68	0.00	68.27	26.84	4.60	0.30	0.00
202	Rehab steel	5	47	57.82	38.15	4.03	0.00	0.00	66.97	17.36	10.66	3.93	1.08
203	Rehab concrete	4	237	45.85	45.55	8.52	0.08	0.00	62.33	22.92	11.79	2.96	0.00
204	Rehab timber	3	0						94.10	5.90	0.00	0.00	0.00
204	Rehab timber	4	18	33.96	59.49	6.56	0.00	0.00	10.80	52.74	26.36	10.10	0.00
205	Rehab masonry	3	30	100.00	0.00	0.00	0.00	0.00	75.45	23.81	0.75	0.00	0.00
205	Rehab masonry	4	3	100.00	0.00	0.00	0.00	0.00	7.16	52.36	23.92	16.56	0.00
206	Rehab MSE	4	31	94.58	0.00	5.42	0.00	0.00	25.88	57.86	15.66	0.60	0.00
211	Rehab joint	3	45	88.57	11.31	0.12	0.00	0.00	33.00	45.83	21.18	0.00	0.00
213	Rehab bearing	3	40	68.60	31.40	0.00	0.00	0.00	73.19	23.47	3.34	0.00	0.00
221	Rehab slope protection	4	143	72.93	26.98	0.09	0.00	0.00	80.66	17.08	2.13	0.14	0.00
222	Rehab channel	4	154	98.70	0.00	1.30	0.00	0.00	61.30	28.34	9.71	0.65	0.00
223	Rehab drainage system	5	0						87.52	11.97	0.51	0.00	0.00
231	Rehab machinery	3	149	93.53	6.47	0.00	0.00	0.00	59.58	23.85	16.57	0.00	0.00
231	Rehab machinery	4	2	0.00	100.00	0.00	0.00	0.00	52.54	20.65	22.28	4.53	0.00
231	Rehab machinery	5	0						51.42	10.74	4.16	29.78	3.90
243	Rehab cable	4	0						91.84	7.03	1.11	0.02	0.00
243	Rehab cable	5	0						49.89	0.11	0.00	48.88	1.13
246	Mudjacking	4	215	95.79	4.21	0.00	0.00	0.00	69.57	28.84	1.59	0.00	0.00
301	Repair deck and substrate	4	0						42.61	24.34	3.70	25.40	3.95
301	Repair deck and substrate	5	82	89.71	9.73	0.56	0.00	0.00	17.53	24.46	21.89	21.62	14.50
302	Spot paint	3	89	91.56	8.44	0.00	0.00	0.00	59.69	38.41	1.90	0.00	0.00
302	Spot paint	4	38	41.96	57.78	0.26	0.00	0.00	65.88	24.27	9.22	0.63	0.00
302	Spot paint	5	805	75.33	17.76	6.83	0.08	0.00	57.25	28.02	9.80	4.35	0.58
303	Clean rebar and patch	4	1974	84.09	0.52	15.39	0.00	0.00	42.10	38.20	17.97	1.73	0.00
311	Repair joint	3	198	62.36	37.64	0.00	0.00	0.00	65.90	28.60	5.50	0.00	0.00
331	Repair/lubricate machinery	3	35	100.00	0.00	0.00	0.00	0.00	51.00	45.01	3.99	0.00	0.00
331	Repair/lubricate machinery	4	271	92.94	7.06	0.00	0.00	0.00	49.95	46.74	3.31	0.00	0.00

By definition, all 100-series replacement actions have a 100% probability of state 1.

By definition, all 400-series routine maintenance actions are not modeled.

Table 4.22. Final recommended effectiveness model

			New model - recommended results				
Action sub-category	States	Usage	State1	State2	State3	State4	State5
201 Rehab deck/replace overlay	4	2	43.88	56.12	0.00	0.00	0.00
201 Rehab deck/replace overlay	5	7	43.88	56.12	0.00	0.00	0.00
202 Rehab steel	4	24	41.03	1.85	56.44	0.68	0.00
202 Rehab steel	5	26	57.82	38.15	4.03	0.00	0.00
203 Rehab concrete	4	28	45.85	45.55	8.52	0.08	0.00
204 Rehab timber	3	1	33.96	59.49	6.56	0.00	0.00
204 Rehab timber	4	41	33.96	59.49	6.56	0.00	0.00
205 Rehab masonry	3	2	100.00	0.00	0.00	0.00	0.00
205 Rehab masonry	4	15	100.00	0.00	0.00	0.00	0.00
206 Rehab MSE	4	3	94.58	0.00	5.42	0.00	0.00
211 Rehab joint	3	7	88.57	11.31	0.12	0.00	0.00
213 Rehab bearing	3	11	68.60	31.40	0.00	0.00	0.00
221 Rehab slope protection	4	3	72.93	26.98	0.09	0.00	0.00
222 Rehab channel	4	4	98.70	0.00	1.30	0.00	0.00
223 Rehab drainage system	5	1	57.82	38.15	4.03	0.00	0.00
231 Rehab machinery	3	22	93.53	6.47	0.00	0.00	0.00
231 Rehab machinery	4	12	93.53	6.47	0.00	0.00	0.00
231 Rehab machinery	5	3	93.53	6.47	0.00	0.00	0.00
243 Rehab cable	4	1	41.03	1.85	56.44	0.68	0.00
243 Rehab cable	5	2	57.82	38.15	4.03	0.00	0.00
246 Mudjacking	4	2	95.79	4.21	0.00	0.00	0.00
301 Repair deck and substrate	4	4	89.71	9.73	0.56	0.00	0.00
301 Repair deck and substrate	5	12	89.71	9.73	0.56	0.00	0.00
302 Spot paint	3	2	91.56	8.44	0.00	0.00	0.00
302 Spot paint	4	30	41.96	57.78	0.26	0.00	0.00
302 Spot paint	5	55	75.33	17.76	6.83	0.08	0.00
303 Clean rebar and patch	4	19	84.09	0.52	15.39	0.00	0.00
311 Repair joint	3	2	62.36	37.64	0.00	0.00	0.00
331 Repair/lubricate machinery	3	2	100.00	0.00	0.00	0.00	0.00
331 Repair/lubricate machinery	4	6	92.94	7.06	0.00	0.00	0.00

By definition, all 100-series replacement actions have a 100% probability of state 1.
By definition, all 400-series routine maintenance actions are not modeled.
Usage = number of Pontis MR&R action definitions that use each action sub-category

4.6 Conclusions

With 14 years of AASHTO CoRe Element bridge inspection experience, Florida DOT has developed one of the first comprehensive bridge deterioration and action effectiveness models based entirely on historical condition state and activity data. The model has very strong statistical characteristics due to its large sample sizes.

As was the case in the 2001 study, the activity data were difficult to process because of unclear categorization of action types, and imprecise dating. Many of the activities were categorized manually. For the others, the available evidence was used in an algorithm to make the best possible guess about the completion date and action type, based on condition data, MMS activity codes, and textual descriptions of activities.

The research developed a new, simplified procedure for estimating one-step Markovian models, that produces usable results with significantly smaller sample sizes than traditional regression. This enabled the estimation of even relatively uncommon elements.

It was found that the new inspection-based models show deterioration rates far slower than the expert elicitation models that have been used to-date. While this had been predicted by practitioners in the field, the magnitude of the discrepancy will be strong motivation for other states to estimate their own statistical models.

Although the statistical evaluation of the deterioration models was strong, the deck and culvert models have characteristics that seem counter-intuitive. Further investigation of these models is warranted to understand why they have such rapid deterioration from condition state 1 to condition state 2. Some manual adjustment may be necessary.

The survival probability concept was investigated for its usefulness in better modeling the onset of deterioration. The Weibull model parameters had the intended effect and appear to improve the overall realism of the models. As a next step, the researchers will test the new model in FDOT's existing Project Level Analysis Tool and Network Analysis Tool to see if the realism and accuracy of programming models is improved.

A new methodology was developed for the estimation of action effectiveness models, which overcomes many of the problems that have been noted in past efforts. A complete set of models was estimated from historical activity and condition data.

This may be an important and timely research effort in the life cycle of AASHTO's Pontis bridge management system. Many states, like Florida, have amassed sizeable databases of condition state inspections, which are large enough to support a similar model estimation effort. The large difference noted here between data-based models and judgment-based models, is likely to be found in other states as well. This should be strong motivation for other states to develop their own models from bridge inspection data.

As design work proceeds on Pontis release 5.2, the designers of the system may find useful techniques, tools, and experiences in this research effort, which will help them improve the capabilities of Pontis in the new release.

5. Validation of Cost Models

This section presents the results from the effort on the gathering and analyses of bridge cost data from FDOT. The primary goal of this research task was to use historical bridge costs to estimate unit costs for use in the Pontis Bridge Management System, specifically, for use at the bridge element action level, and also compare the results with those costs currently used in the Pontis BMS and PLAT.

5.1 Data Background

Cost data were obtained through three main sources: Statewide Bid History on Bridge-related Construction Projects; FDOT District Two Bid records on Bridge-related Construction Projects; and merge of two state-maintained databases on historical cost data on bridge maintenance and repair at FDOT, i.e., the Bridge Work Library, and the MMS Site Cost data.

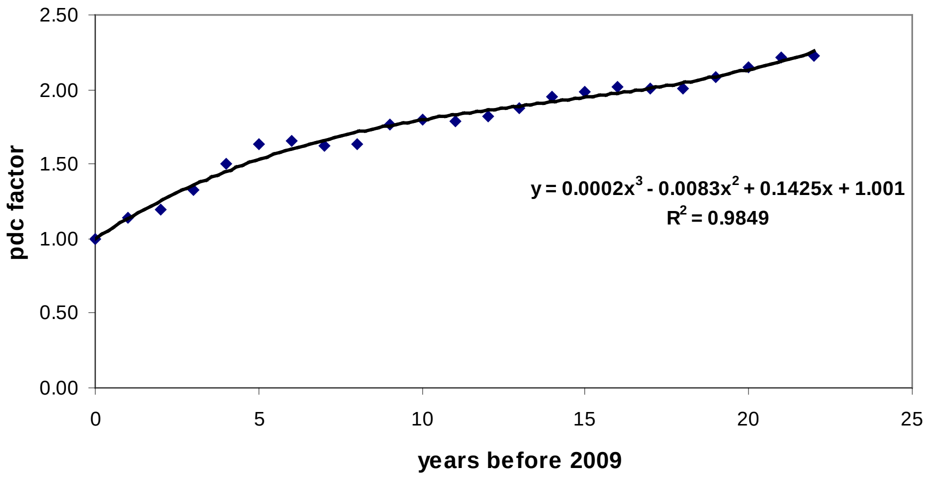
Due to inflation of prices and other economic factors, there is a typical increase in the cost of commodities relative to time. The most common illustration of this is the consumer price index or the popular cost indexes. There are several cost indexes available for highway construction costs but the FDOT has a directly usable set of factors. FDOT published a report on advisory inflation factors, which lists a set of cost inflation factors, commonly referred to as the Present Day Cost (PDC) multipliers (FDOT 2009). The PDC multipliers, as well as the equivalent cost index computed in this study, are shown in Figure 5.1. The PDC multipliers are based on estimates for cost inflation on the national level, with particular emphasis on the Producer Price Index for Highway and Street Construction, which is reported by the U.S. Department of Labor’s Bureau of Labor Statistics. As shown in Figure 5.1, a regression equation was established with factors to estimate 2009 costs, given how many years a cost was incurred prior to 2009, These factors were used in this study to adjust the costs to 2009 equivalent or current costs, from the costs originally incurred in previous years.

5.2 Bridge Costs from Statewide Bid Records

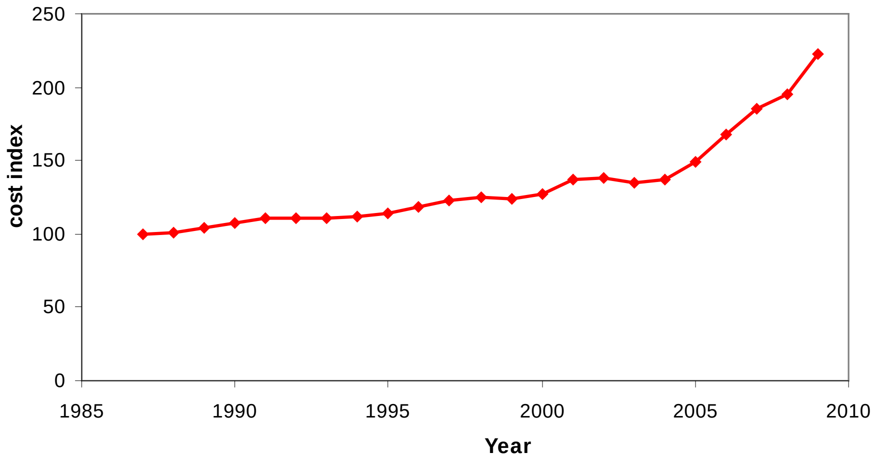
The main source of statewide bid data was the AASHTO Trns●port Database, used by FDOT for storing construction bid records. Using the bridge project bid records for the lettings of years 2005 through 2008, project descriptions were considered, as well as review of the bid items, to ascertain the type of work. Bridge widening and replacement or new bridges were typically clearly indicated in the project summary labels (Figure 5.2). Major rehabilitation was also typically indicated, especially for superstructure-related work, in the database but some cases were specific enough to be able to classify the work as rehabilitation on movable bridge, fender, substructure, etc. These specific classes were assigned accordingly, resolving any conflict between the summary labels and the list of pay items by relying more on the list of pay items. Rehabilitation projects with relatively low costs, most with costs less than $40,000 (before time factor adjustment) were grouped under minor rehabilitation. It should be noted that the classifications were not necessarily exclusive to the titled work type. For instance, bridge widening projects often include pay items to correct structural deficiencies on the bridge.

To obtain the 2009 dollars equivalent, the FDOT PDC factors were used to convert the total project cost and the cost of listed bid items. The means and standard deviations of the costs in both Metric and English units are presented in Tables 5.1 to 5.4, as well as other pertinent basic descriptive statistics. The 2007 bridge and roadway inventory from the Pontis database was used to obtain the pertinent bridge and roadway attributes. Using these attributes, unit costs of the various types of work can be estimated, as well as investigating relationships between costs and the bridge attributes.

As shown in Table 5.2, new bridges appear to cost generally about $260/SF to build while new bridges on the interchanges and non-interchanges cost just under $250/SF and $265/SF respectively. Major rehabilitation projects cost about $53/SF. Fender rehabilitation cost about $22/SF, cathodic protection projects cost about $11/SF of bridge deck area, and riprap projects were estimated as just under $40/SF. Bridge painting was estimated to cost about $21/SF and painting done with other repairs on the bridge cost about $28/SF. Minor rehabilitation costs an estimated $2.65/SF, while Deck joint construction and rehabilitation costs $3.01/SF and $1.65/SF respectively.



a. PDC Multiplier

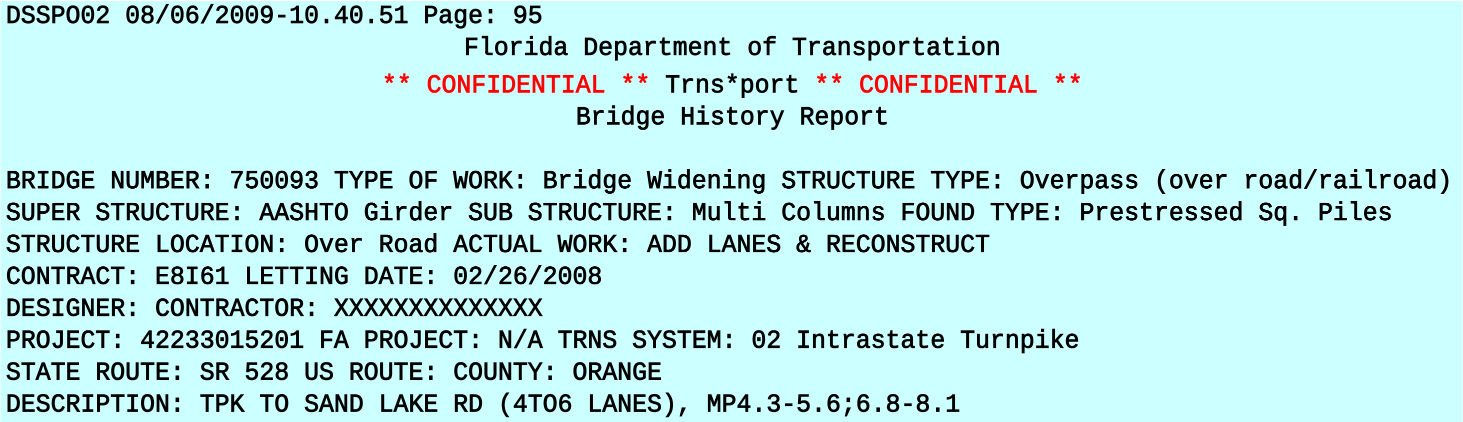


b. Cost Index

Year	PDC Multiplier	Equivalent Cost Index*
1987	2.23	100
1988	2.21	101
1989	2.15	104
1990	2.08	107
1991	2.01	111
1992	2.01	111
1993	2.02	110
1994	1.99	112
1995	1.95	114
1996	1.88	119
1997	1.82	123
1998	1.79	125
1999	1.80	124
2000	1.76	127
2001	1.63	137
2002	1.62	138
2003	1.66	134
2004	1.63	137
2005	1.50	149
2006	1.33	168
2007	1.20	186
2008	1.14	196
2009	1.00	223

* Base 1987 = 100

Figure 5.1. Trend of FDOT PDC Time Factor Multiplier (2009 = 1) and Cost Index (1987 = 100)



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DSSPO02 08/06/2009-10.40.51 Page: 95
                              Florida Department of Transportation
                        ** CONFIDENTIAL ** Trns*port ** CONFIDENTIAL **
                                      Bridge History Report

BRIDGE NUMBER: 750093 TYPE OF WORK: Bridge Widening STRUCTURE TYPE: Overpass (over road/railroad)
SUPER STRUCTURE: AASHTO Girder SUB STRUCTURE: Multi Columns FOUND TYPE: Prestressed Sq. Piles
STRUCTURE LOCATION: Over Road ACTUAL WORK: ADD LANES & RECONSTRUCT
CONTRACT: E8I61 LETTING DATE: 02/26/2008
DESIGNER: CONTRACTOR: XXXXXXXXXXXXXX
PROJECT: 42233015201 FA PROJECT: N/A TRNS SYSTEM: 02 Intrastate Turnpike
STATE ROUTE: SR 528 US ROUTE: COUNTY: ORANGE
DESCRIPTION: TPK TO SAND LAKE RD (4TO6 LANES), MP4.3-5.6;6.8-8.1
```

Figure 5.2. Sample summary section from Trns*port database reports

Some costs are better expressed relative to bridge length. For instance, bridge widening cost about $106/SF based on the original deck area and using the deck area in the 2007 bridge inventory. So given that the bridge length will most likely remain the same, the bridge widening cost can be said to be about $6,400/LF of bridge length. It can also be assumed that the widening is always done to make the bridge functionally adequate, i.e., to the adequate new width. Similarly, the costs of painting, railing, deck joint construction, and deck joint rehabilitation, which can also be reasonably related to the bridge length, are also estimated approximately as $1,100/LF, $1,800/LF, $220/LF, and $73/LF respectively. The parameters shown in Tables 5.1 to 5.4 indicate to some extent, the statistical distribution of these cost estimates, i.e., the mean (point estimate), skewness, spread (standard deviation), etc.

In estimating the unit cost of bridge widening projects, a further step was taken by reviewing the bridge inventory records for the various years to identify, for the listed projects, if and when changes were recorded for the bridge deck widths accordingly. Out of the 78 widening projects, only 18 were identified as having an increase in bridge width shown on the bridge records. The primary reason for the lack of the changed widths for the other records was that these projects are recent; many of the widening projects being reviewed were let for bidding in 2007 and 2008, thus the projects may have not been completed or if completed, have not been entered yet into the bridge inventory database. The data for the 18 projects are shown in Table 5.5. The traffic volumes, assumed not to have changed significantly over the years, are based on the 2007 inventory data. Some simple statistical analyses done on the data showed that the mean unit cost of bridge widening is about $3,400 per sq. meter or just under $320 per sq. feet of added deck area. Figure 5.3 shows the variation in the unit cost, with most unit costs between $200/SF and $400/SF, and about 95% of the costs observed as being less than or equal to $400/SF.

The influence of bridge and roadway attributes on the unit cost were also investigated, including bridge length, traffic volume or ADT, and the added deck area. The influences were not indicated as being very strong. An example is shown in Figure 5.4, for the added deck area, indicating that this factor (with R^2 equal to 0.27) cannot be used to completely explain the variation in unit costs of bridge widening. But it is good to know that the more deck area you add, the cheaper it becomes in terms of the unit costs. It was also estimated that, based on these 18 identified projects, the bridges were widened on the average of additional deck width of 8.0 meter or 26.2 feet (standard deviation of 6.6 meter or 21.7 feet.), and an average additional deck area of 481.3 sq. meter or 5,178.9 sq. feet (standard deviation of 284.7 sq. meter or 3,063.7 sq. feet). Statistical distributions of the cost estimates are also illustrated in Figures 5.5 and 5.6 where the unit costs for the following work types are compared: new bridge versus bridge rehabilitation projects; and joint rehabilitation versus joint replacement (new construction) projects.

Table 5.1. Summary of FDOT bridge project costs per deck area (metric units)

	COSTS PER DECK AREA ($/SQ. M)					No. of Projects
Type of Work	MEAN	STD. DEV	MIN	MAX	MEDIAN	
Cathodic Protection	121.46	148.77	6.95	489.21	63.61	14
Fender	217.59	378.95	2.89	1,547.09	69.48	18
Deck Joint Construction	32.43	10.48	18.15	51.46	30.11	14
Deck Joint Rehabilitation	17.44	28.75	0.76	162.52	9.97	58
Major Rehabilitation*	571.70	839.90	4.78	3,764.09	256.93	86
Major Rehabilitation - Interchange	1,339.84	714.72	612.83	2,456.67	1,281.37	6
New Bridge/Replace	2,843.74	1,138.26	1,111.36	6,749.99	2,544.62	34
New Bridge - Interchange	2,674.74	1,366.59	1,405.48	6,471.59	2,188.08	12
New Bridge/Replace - All	2,799.65	1,188.40	1,111.36	6,749.99	2,527.20	46
Painting	228.29	265.30	16.55	1,040.43	162.05	16
Painting with Repairs	302.15	424.83	55.70	1,154.64	134.37	6
Railing	100.13	68.85	1.14	252.30	88.68	25
Railing with Joints, Fence, or Misc.	143.75	102.41	13.44	417.42	149.86	21
Minor Rehabilitation	28.52	42.27	0.73	252.24	13.68	93
Major Rehabilitation - Movable	732.49	866.47	91.40	2,501.75	326.46	8
Major Rehabilitation - Substructure	464.57	660.24	28.97	1,902.16	226.40	7
Riprap	422.61	237.41	155.53	752.20	410.94	8
Widening[#]	1,146.22	675.39	73.10	3,607.85	1,003.15	78
Widening[##]	3,422.74	1,229.03	650.08	7,019.18	3,587.19	18
Widening - Interchange	566.56	343.76	274.36	945.32	479.98	3

* majority are superstructure related.

[#] Estimated based on entire deck area.

[##] Estimated based on added deck area.

Table 5.2. Summary of FDOT bridge project costs per deck area (English units)

	COSTS PER DECK AREA ($/SF)					No. of Projects
Type of Work	MEAN	STD. DEV	MIN	MAX	MEDIAN	
Cathodic Protection	11.29	13.83	0.65	45.47	5.91	14
Fender	20.22	35.22	0.27	143.78	6.46	18
Deck Joint Construction	3.01	0.97	1.69	4.78	2.80	14
Deck Joint Rehabilitation	1.62	2.67	0.07	15.10	0.93	58
Major Rehabilitation*	53.13	78.06	0.44	349.82	23.88	86
Major Rehabilitation - Interchange	124.52	66.42	56.95	228.32	119.09	6
New Bridge/Replace	264.29	105.79	103.29	627.32	236.49	34
New Bridge - Interchange	248.58	127.01	130.62	601.45	203.35	12
New Bridge/Replace - All	260.19	110.45	103.29	627.32	234.87	46
Painting	21.22	24.66	1.54	96.69	15.06	16
Painting with Repairs	28.08	39.48	5.18	107.31	12.49	6
Railing	9.31	6.40	0.11	23.45	8.24	25
Railing with Joints, Fence, or Misc.	13.36	9.52	1.25	38.79	13.93	21
Minor Rehabilitation	2.65	3.93	0.07	23.44	1.27	93
Major Rehabilitation - Movable	68.08	80.53	8.49	232.50	30.34	8
Major Rehabilitation - Substructure	43.18	61.36	2.69	176.78	21.04	7
Riprap	39.28	22.06	14.45	69.91	38.19	8
Widening[#]	106.53	62.77	6.79	335.30	93.23	78
Widening[##]	318.10	114.22	60.42	652.34	333.38	18
Widening - Interchange	52.65	31.95	25.50	87.86	44.61	3

* majority are superstructure related.

[#] Estimated based on entire deck area.

[##] Estimated based on added deck area.

Table 5.3. Summary of FDOT bridge project costs per length (metric units)

	COSTS PER BRIDGE LENGTH ($/M)					No. of Projects
Type of Work	MEAN	STD. DEV	MIN	MAX	MEDIAN	
Cathodic Protection	1,482.88	1,674.61	123.09	5,576.81	765.80	14
Fender	3,475.00	6,081.87	124.42	20,951.71	993.28	18
Deck Joint Construction	721.25	282.01	479.07	1,360.02	642.57	14
Deck Joint Rehabilitation	239.45	307.95	15.43	1,546.85	129.20	58
Major Rehabilitation*	9,094.70	13,049.95	62.23	65,212.34	4,255.05	86
Major Rehabilitation - Interchange	23,616.12	13,427.09	10,891.16	46,176.09	20,427.78	6
New Bridge/Replace	45,040.80	22,540.02	20,907.87	117,436.15	35,468.90	34
New Bridge - Interchange	39,639.60	20,204.22	19,599.41	85,016.43	35,473.99	12
New Bridge/Replace - All	43,631.79	21,865.65	19,599.41	117,436.15	35,468.90	46
Painting	3,556.97	4,853.81	217.45	20,010.45	2,495.69	16
Painting with Repairs	5,900.59	8,573.38	679.34	22,981.32	3,079.15	6
Railing	1,234.22	686.06	14.67	2,749.43	1,171.32	25
Railing with Joints, Fence, or Misc.	1,938.34	1,252.87	173.37	4,817.37	1,988.87	21
Minor Rehabilitation	450.04	740.43	14.19	3,631.37	167.84	93
Major Rehabilitation - Movable	8,654.94	9,146.01	1,137.90	26,686.43	5,619.36	8
Major Rehabilitation - Substructure	5,405.28	4,711.01	378.79	14,785.02	4,490.34	7
Riprap	5,604.40	3,159.27	1,574.57	9,305.45	6,539.30	8
Widening	21,028.54	13,871.46	2,822.20	86,054.72	17,680.42	78
Widening - Interchange	16,270.91	9,138.19	8,982.83	26,523.24	13,306.65	3

* majority are superstructure related.

Table 5.4. Summary of FDOT bridge project costs per length (English units)

	COSTS PER BRIDGE LENGTH ($/LF)					No. of Projects
Type of Work	MEAN	STD. DEV	MIN	MAX	MEDIAN	
Cathodic Protection	452.10	510.55	37.53	1,700.25	233.47	14
Fender	1,059.45	1,854.23	37.93	6,387.72	302.83	18
Deck Joint Construction	219.89	85.98	146.06	414.64	195.91	14
Deck Joint Rehabilitation	73.00	93.89	4.70	471.60	39.39	58
Major Rehabilitation*	2,772.78	3,978.64	18.97	19,881.81	1,297.27	86
Major Rehabilitation - Interchange	7,200.04	4,093.63	3,320.48	14,078.08	6,227.98	6
New Bridge/Replace	13,731.95	6,871.96	6,374.35	35,803.70	10,813.69	34
New Bridge - Interchange	12,085.24	6,159.82	5,975.43	25,919.64	10,815.24	12
New Bridge/Replace - All	13,302.37	6,666.36	5,975.43	35,803.70	10,813.69	46
Painting	1,084.44	1,479.82	66.29	6,100.75	760.88	16
Painting with Repairs	1,798.96	2,613.83	207.12	7,006.50	938.77	6
Railing	376.29	209.16	4.47	838.24	357.11	25
Railing with Joints, Fence, or Misc.	590.96	381.97	52.86	1,468.71	606.36	21
Minor Rehabilitation	137.21	225.74	4.33	1,107.13	51.17	93
Major Rehabilitation - Movable	2,638.70	2,788.42	346.92	8,136.11	1,713.22	8
Major Rehabilitation - Substructure	1,647.95	1,436.28	115.49	4,507.63	1,369.01	7
Riprap	1,708.66	963.19	480.05	2,837.03	1,993.69	8
Widening	6,411.14	4,229.10	860.43	26,236.20	5,390.37	78
Widening - Interchange	4,960.64	2,786.03	2,738.67	8,086.35	4,056.91	3

* majority are superstructure related.

Table 5.5. Data on bridge widening projects showing added deck width and area

Bridge No.	Year of Width Change*	Project Bid Let Year	Bridge Length (M)	Change in Bridge Deck Width (M)	Added Bridge Deck Area (Sq. M)	Project Cost (2009 $)	Unit Cost ($/Sq. M)	Unit Cost ($/SF)	Traffic Volume ADT (veh/day)
140061	2009	2005	47.8	7.7	368.1	1,323,083.47	3,594.75	334.08	39,250
550046	2009	2006	44.8	4.9	219.5	835,159.08	3,804.48	353.58	25,250
550047	2009	2006	44.8	4.9	219.5	789,581.03	3,596.85	334.28	25,250
550048	2009	2006	37.7	4.9	184.7	650,024.49	3,518.78	327.02	25,250
550049	2009	2006	37.7	4.9	184.7	669,348.91	3,623.39	336.75	25,250
550068	2009	2006	113.9	5.3	603.7	2,387,389.13	3,954.79	367.55	21,250
550074	2009	2006	67.2	4.9	329.3	899,536.23	2,731.83	253.89	18,750
550076	2008	2006	92.6	3.0	277.8	1,949,927.80	7,019.18	652.34	44,500
550085	2009	2006	113.9	5.3	603.7	2,422,834.89	4,013.51	373.00	21,250
550090	2009	2006	67.2	4.9	329.3	885,651.66	2,689.66	249.97	18,750
550092	2009	2006	42.7	8.4	358.7	1,437,034.97	4,006.45	372.35	31,000
550093	2009	2006	42.7	8.4	358.7	1,451,071.01	4,045.59	375.98	31,000
750092	2008	2005	108.2	6.1	660.0	1,595,264.51	2,416.99	224.63	33,700
750219	2008	2005	108.2	5.2	562.6	1,631,711.39	2,900.10	269.53	33,700
750294	2008	2005	81.1	4.8	389.3	1,174,021.15	3,015.88	280.29	22,250
770035	2009	2007	35.6	27.9	993.2	645,687.13	650.08	60.42	44,000
860432	2009	2005	124.4	9.2	1,144.5	4,096,811.43	3,579.63	332.68	116,200
930319	2008	2005	38.1	23.0	876.3	2,144,652.73	2,447.40	227.45	14,750

*Year indicated in the FDOT bridge inventory for change in bridge width

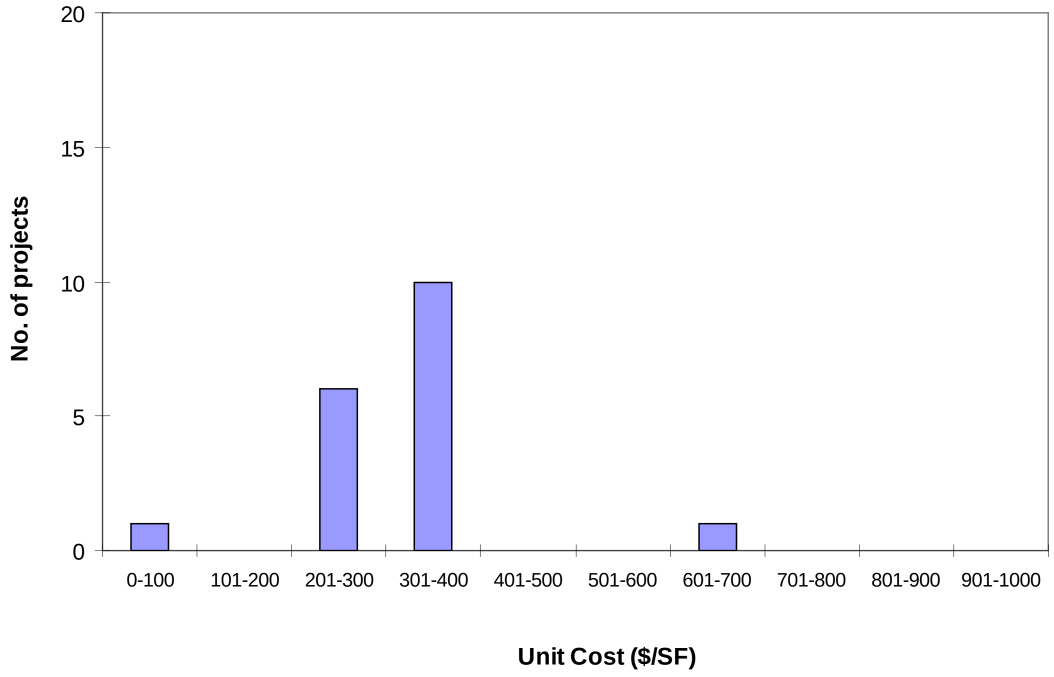


Figure 5.3. Variation in bridge widening unit costs (18 projects) estimated based on the added deck area (SF)

Figure 5.4. Variation in bridge widening unit costs (18 projects) relative to the added deck area (SF)

Analyses of the individual item bids under each project were also done to identify specific bid items that are directly applicable to bridge maintenance and rehabilitation. There are several bid items identified, as shown as in Tables 5.6 and 5.7.

Using a methodology similar to that employed during the FDOT agency cost study, an Action Subcategory (ActSubCat) was assigned to each bid item. These are codes that make the identified work compatible with bridge element actions in the Pontis bridge management system (Sobanjo and Thompson 2002). Looking at Tables 5.6 and 5.7, bridge deck expansion joint for new construction (Action Subcategory No. 111) and expansion joint seal (Action Subcategory No. 112) were estimated to cost about $81/LF and $130/LF respectively, while deck joint rehabilitation cost about $86/LF. Concrete slope pavement (4”, non-reinforced) cost about $107/SY. Cleaning and sealing deck joints cost about $79/LF while cleaning and resealing concrete pavements cost about $100/LF. Railings and handrails cost about $160/LF. Painting structural steel cost about $4,600/TN while bearing assemblies cost about $5,800 each. “”Restoring spalled areas,” a very common maintenance activity on concrete bridges, cost just over $1,000/CF. The cost of “Concrete surfaces cleaning and coating” was estimated as $7.18/SF but this estimate includes some extreme large values; if the largest 10% of the data is excluded (using only data within the 90th percentile of $10/SF) the estimate is $1.82/SF. Mobilization and Maintenance of Traffic costs were estimated as about $251,000 lump sum and $470/Day respectively, but the values vary for the various types of bridge work as shown in Table 5.6. The statistical distribution of the bid item cost of the deck joint rehabilitation and concrete slope pavement are shown in Figures 5.7 and 5.8. Though with a few large extreme values, the real limits of the estimates can be observed in the distributions shown. Generally, for the work types and bid items with large data sizes, these project cost estimates as shown in Tables 5.1 to 5.7, can be considered statistically acceptable. Even for those with small data sizes, such as riprap, these values are also useful given that this type of work is not done that frequently.

Table 5.6. List of FDOT bridge project bid item unit costs for element replacement actions (English units)

			UNIT COSTS ($/UNIT)					No. of
ActSubCat	Bid Item Description	UNIT	MEAN	STD. DEV	MIN	MAX	MEDIAN	Bids
102	PAINT STRUCT STEEL (CABLES)	LF	99.89	6.71	95.14	104.63	99.89	2
102	PAINTING STRUCTURAL STEEL	TN	4,584.74	8,992.11	200.70	46,835.25	1,733.38	28
111	BRIDGE DECK EXPANSION JOINT, NEW CONSTRUCTION, F&I	LF	80.53	85.55	29.57	283.85	47.23	15
111	FINGER JOINT	LF	3,436.50	2,937.75	1,359.20	5,513.80	3,436.50	2
112	ELASTIC PREFORMED JOINT SEAL (NO NOSING)	LF	118.37	110.23	14.51	261.18	58.26	13
112	EXPANSION JOINT SEAL	LF	130.01	175.46	46.21	870.60	65.30	46
113	COMPOSITE NEOPRENE PADS	CF	2,198.45	7,063.77	725.50	72,550.00	1,373.83	102
113	MULTIROTATIONAL BEARING ASSEMBLY	EA	5,769.86	2,660.48	3,047.10	14,510.00	4,933.40	17
113	NEOPRENE PAD REPLACEMENT, BENT/PIER	EA	4,644.69	3,047.08	1,547.55	8,560.90	5,677.00	5
114	ALUMINUM RAILINGS (VARIOUS)	LF	77.44	46.35	35.99	275.69	73.31	34
114	CONCRETE TRAFFIC RAILING BARRIER (BRIDGE)(VARIOUS)	LF	156.78	87.44	49.70	627.20	135.92	127
114	CONCRETE TRAFFIC RAILING-BRIDGE, (32" F - SHAPE AND OTHERS)	LF	196.88	553.89	74.94	5,017.60	105.37	79
114	METAL TRAFFIC RAILING (STEEL POST & RAIL; THRIE BEAM RETROFIT)	LF	168.87	93.78	83.45	334.26	127.16	13
114	METAL TRAFFIC RAILING BARRIER (STEEL POST & RAIL; THRIE BEAM RETROFIT)	LF	212.37	91.21	74.08	407.76	217.65	11
114	PEDESTRIAN/BICYCLE RAILING (VARIOUS METALS)	LF	124.60	63.62	67.96	362.75	111.47	24
114	PIPE HANDRAIL (VARIOUS)	LF	181.32	225.66	29.02	672.80	87.81	7
114	RAILINGS AND HANDRAILS, ALL	LF	159.53	296.80	29.02	5,017.60	116.08	296
121	CONCRETE SLOPE PAVEMENT,NON REINFORCED, 4"	SY	107.47	70.10	45.16	470.40	82.71	53
121	SLOPE PAVT CONC (4")(REINFORCED)	SY	77.12	36.61	45.42	108.83	77.12	4
123	BRIDGE DRAINAGE PIPING	LF	108.75	30.49	87.06	165.77	87.06	7
123	BRIDGE DRAINS	EA	2,553.67	1,073.16	170.31	3,623.96	2,902.00	10
132	CATHODIC PROTECTION SYSTEM (ZINC/TITANUM SPRAY OR SHEET)	SF	194.07	486.79	15.90	2,176.50	60.94	19
132	CATHODIC PROTECTION, F&I, PILE, ZINC ANODE ASSEMBLY	EA	1,193.89	581.66	569.21	2,547.96	1,197.08	11
132	CATHODIC PROTECTION-INTEGRAL PILE JACKET, GALVANIC,	LF	1,674.81	309.39	1,133.98	2,009.66	1,831.42	12
141	PRESTRESSED BEAMS (VARIOUS)	LF	293.88	214.19	100.93	1,596.10	245.17	126
151	MOVABLE BRIDGE SIGNAL(FUR&INS)	AS	35,214.00	16,979.05	15,680.00	46,432.00	43,530.00	3
151	SIGN LT'D OVHD TRUSS (T 21 TO 40,S 101 TO 200)	AS	68,922.50	5,130.06	65,295.00	72,550.00	68,922.50	2

Table 5.7. List of FDOT bridge project bid item unit costs for rehab, repair, maintenance and general actions (English units)

			UNIT COSTS ($/UNIT)					No. of
ActSubCat	Bid Item Description	UNIT	MEAN	STD. DEV	MIN	MAX	MEDIAN	Bids
211	BRIDGE DECK EXPANSION JOINT, REHABILITATION, VARIOUS	LF	85.75	118.59	28.37	889.37	49.96	99
221	CLEANING & RESEALING JOINTS- CONCRETE PAVEMENT	LF	99.61	89.63	29.02	365.65	79.81	12
221	CRACKS INJECT & SEAL	LF	166.49	311.14	12.91	1,673.47	94.08	27
221	RIPRAP (RUBBLE) (F&I)(DITCH LINING)	TN	184.15	215.51	75.45	623.35	101.53	6
221	RIPRAP FABRIC-FORMED CONCRETE (8" FILTER POINTS)	TN	120.67	34.94	73.13	191.53	118.58	8
221	RIPRAP, SAND-CEMENT	CY	1,015.41	654.55	198.70	2,333.18	787.90	36
244	BRIDGE FENDER SYSTEM REMOVAL & DISPOSAL	LF	686.04	487.31	130.59	1,664.77	584.17	12
244	FENDER SYSTEM,PLASTIC MARINE LUMBER, REINFORCED OR NON-REINFORCED	MB	16,669.74	7,371.58	940.80	25,088.00	18,376.96	10
251	SIGN EXISTING (RELOCATEOR REMOVE)	AS	10,812.00	12,253.65	174.12	29,020.00	7,255.00	5
303	SPALLED AREAS RESTORE (VARIOUS)	CF	1,053.92	1,274.55	1.14	7,865.69	689.92	57
311	CLEAN & SEAL JOINTS(STRUCTURES / REHAB / WIDENING)	LF	78.62	69.71	14.53	167.18	37.55	11
341	BEAMS REPAIR	LF	3,986.53	3,973.19	1,177.07	6,796.00	3,986.53	2
400	ANTI-GRAFFITI COATING (SACRIFICIAL NON SACRIFICIAL)	SF	0.66	0.47	0.29	1.45	0.48	21
400	PROTECTION OF EXISTING STRUCTURES	LS	33,012.55	58,187.77	579.05	377,260.00	14,760.20	43
400	PROTECTION OF EXISTING STRUCTURES (WIDEN)	LS	31,611.07	67,553.63	579.05	377,260.00	14,510.00	30
400	REMOVAL OF EXISTING STRUCTURE (ALL)	SF	348.23	1,370.37	1.49	10,035.20	66.94	73
400	REMOVAL OF EXISTING STRUCTURE (WIDEN)	SF	103.10	93.04	4.72	385.12	66.56	44
403	CONCRETE SURFACES CLEANING & COATING	SF	7.16	23.95	0.38	196.88	1.36	98
403	CONCRETE SURFACES CLEANING & COATING (BELOW 90TH %LE of $10/SF)	SF	1.82	1.50	0.38	9.58	1.24	90
	MAINTENANCE OF TRAFFIC (ALL)	DA	466.37	721.24	17.18	3,917.13	205.00	48
	MAINTENANCE OF TRAFFIC (CATHODIC PROTECTION)	DA	302.65	164.53	163.24	483.67	281.85	4
	MAINTENANCE OF TRAFFIC (FENDER)	DA	317.89	165.95	17.18	501.76	355.98	7
	MAINTENANCE OF TRAFFIC (MAJOR REHAB)	DA	691.94	940.72	60.82	3,917.13	209.07	25
	MAINTENANCE OF TRAFFIC (PAINTING/REPAIRS)	DA	92.33	79.30	17.42	226.37	75.69	5
	MAINTENANCE OF TRAFFIC (RIRAP)	DA	169.95	122.63	81.75	341.74	81.75	7
	MOBILIZATION (ALL)	LS	251,486.10	423,840.29	6,272.00	1,523,550.00	85,155.00	49
	MOBILIZATION (CATHODIC PROTECTION)	LS	88,772.85	68,500.55	14,510.00	173,716.41	83,432.50	4
	MOBILIZATION (FENDER)	LS	94,636.86	77,288.22	27,184.00	259,383.82	75,802.58	7
	MOBILIZATION (MAJOR REHAB)	LS	379,752.42	488,126.20	14,510.00	1,523,550.00	143,406.47	25
	MOBILIZATION (PAINTING/REPAIRS)	LS	309,703.05	663,744.35	6,272.00	1,497,010.65	15,895.60	5
	MOBILIZATION (RIPRAP)	LS	31,399.16	23,641.41	14,476.35	75,264.00	14,476.35	7

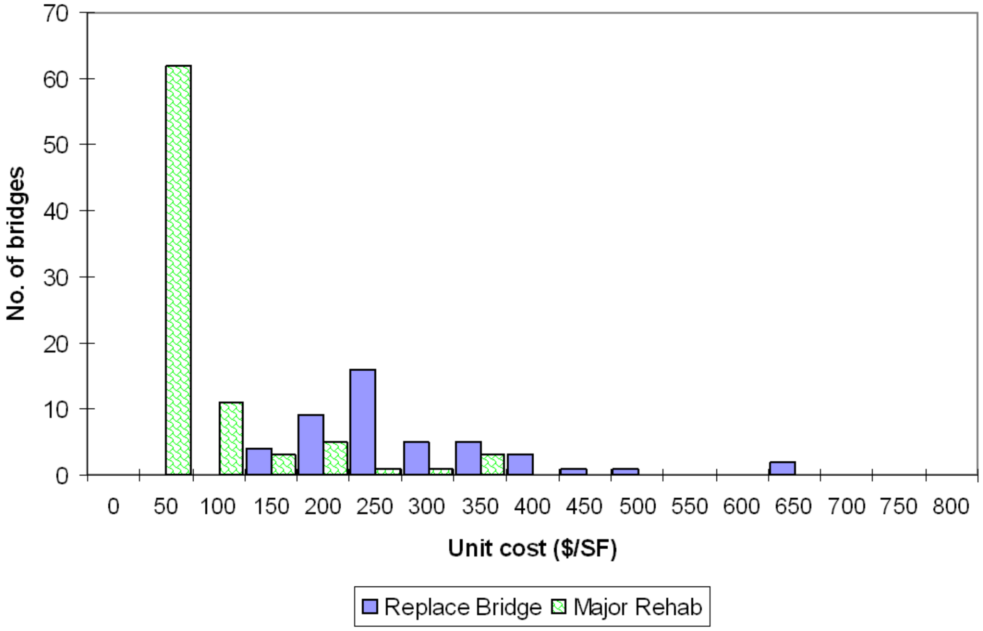


Figure 5.5. Comparison of the distributions of project unit costs of bridge replacement and major rehabilitation

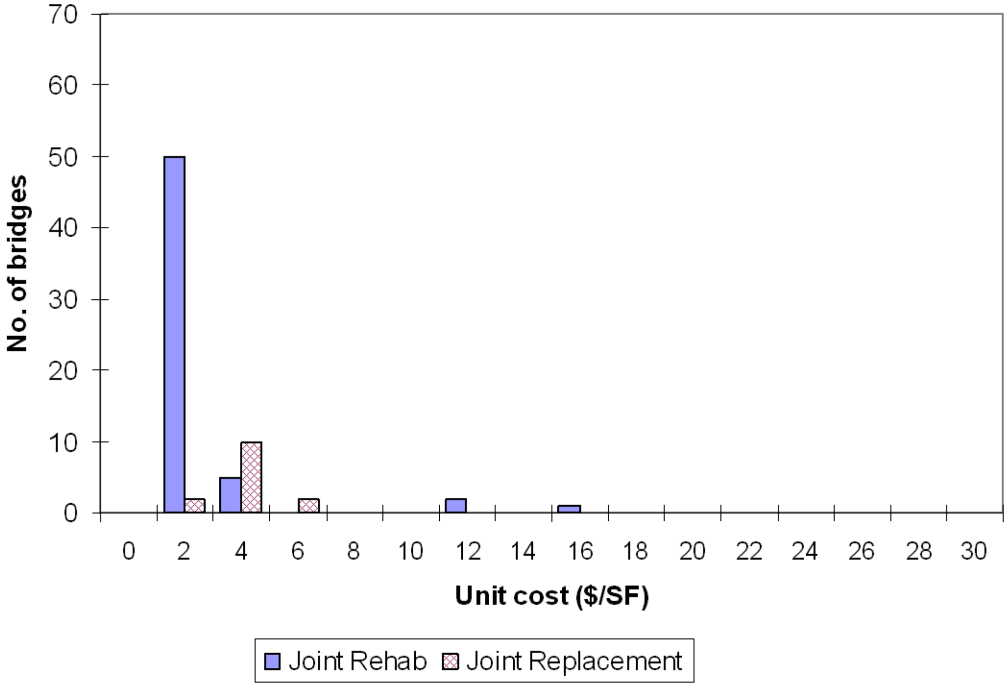


Figure 5.6. Comparison of the distributions of project unit costs of bridge deck joint rehabilitation and joint replacement

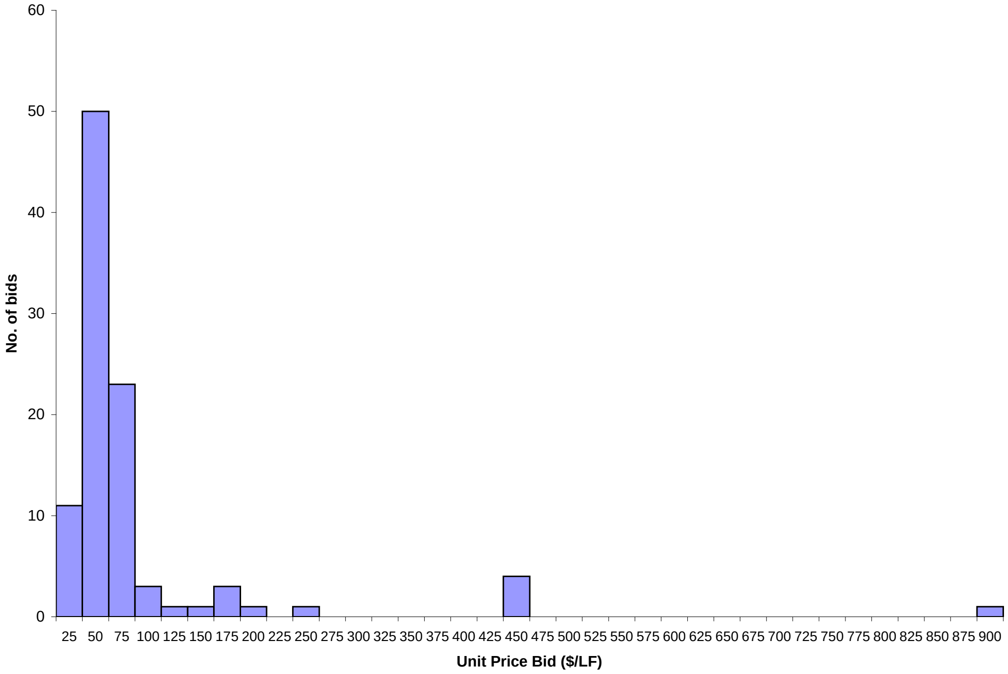


Figure 5.7. Variation in item unit price bids for “Bridge Deck Expansion Joint, Rehabilitation, Various.”

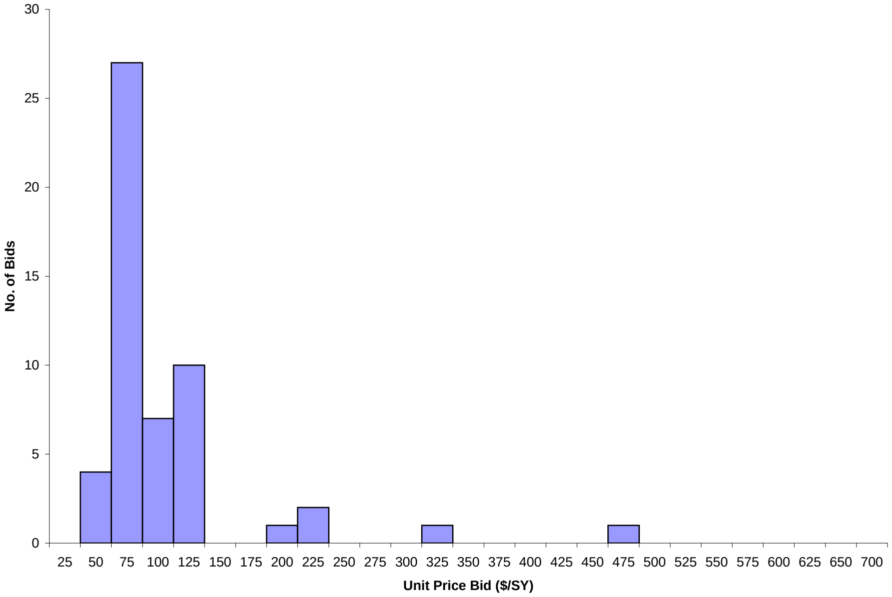


Figure 5.8. Variation in item unit price bids for “Concrete Slope Pavement, Non Reinforced, 4"”

Based on the inventory data, an investigation was conducted to identify relationships between the estimated costs and the bridge and roadway attributes. Some of the findings, with reasonable correlation or coefficients of determination (R^2), though not perfect, are presented in Figures 5.9 to 5.16. Project costs of cathodic protection (Figure 5.9), deck joint replacement (Figure 5.11), widening (Figure 5.16), and new bridge/replacement projects (Figure 5.18), were observed to increase with increase in bridge length. Costs of new bridge/replacement projects (Figure 5.18) and deck joint rehabilitation (Figure 5.12) increased also with increase in deck area. The effect of age of the bridge at the time of action was also found to be influential. The age was computed by assuming an average of two years for the completion of construction after the bid letting date. This assumption was validated using the new bridge construction projects by comparing the estimated completion dates with the "year built" information in the bridge inventory data. For fender rehabilitation (Figure 5.10) and deck joint rehabilitation projects (Figure 5.12), older bridges have higher costs. Minor rehabilitation projects costs tend to increase with an increase in the amount of traffic carried (Figure 5.14). Finally, as shown in Figure 5.19, the Maintenance of Traffic (MOT) costs increase with the number of days (item quantity) it is being used.

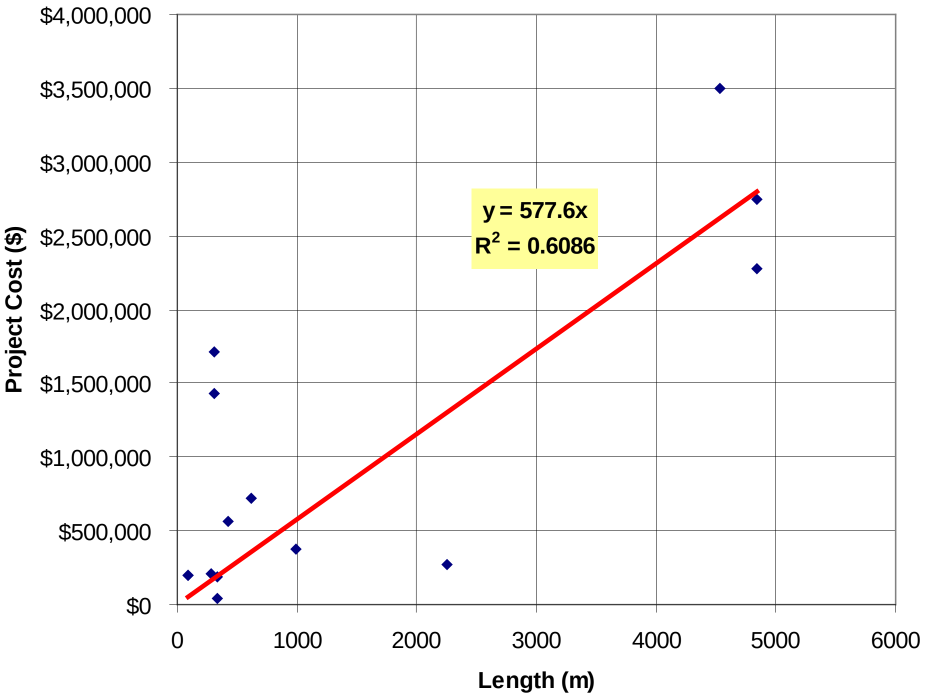


Figure 5.9. Variation in bridge cathodic protection project costs relative to bridge length

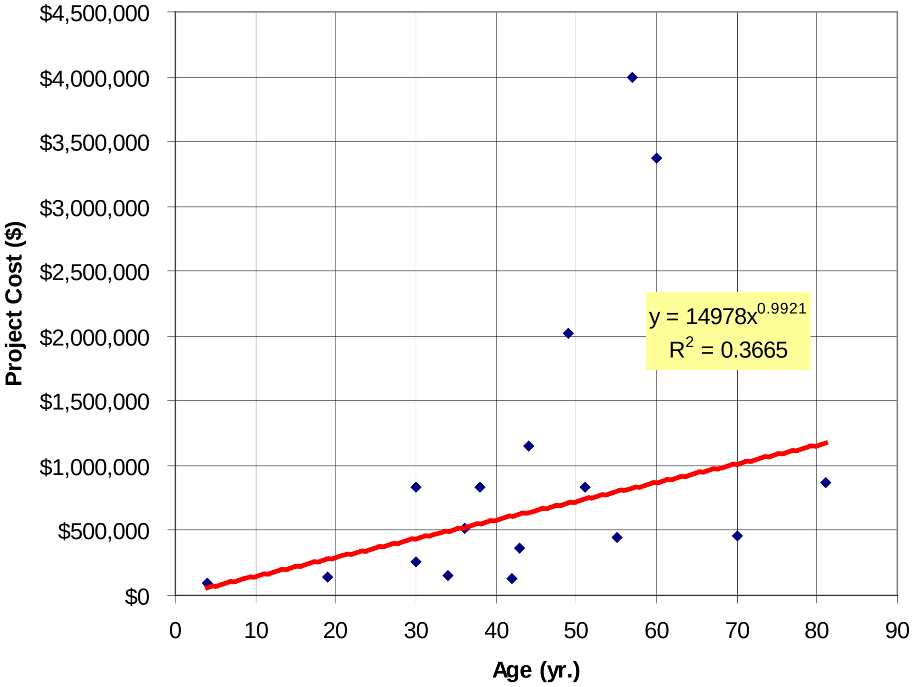


Figure 5.10. Variation in bridge fender rehabilitation project total costs relative to age

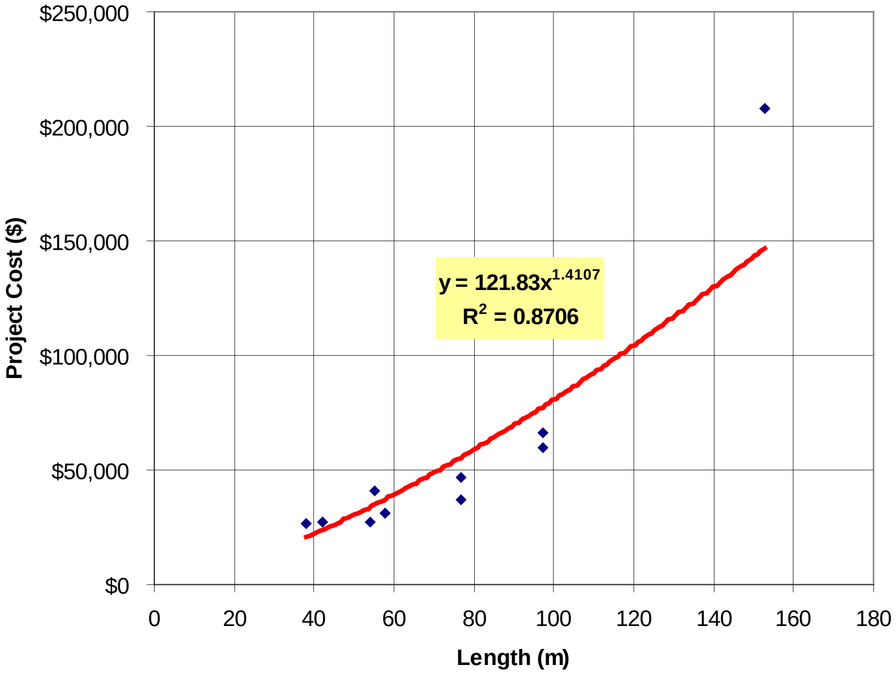


Figure 5.11. Variation in bridge joint replacement project costs relative to bridge length

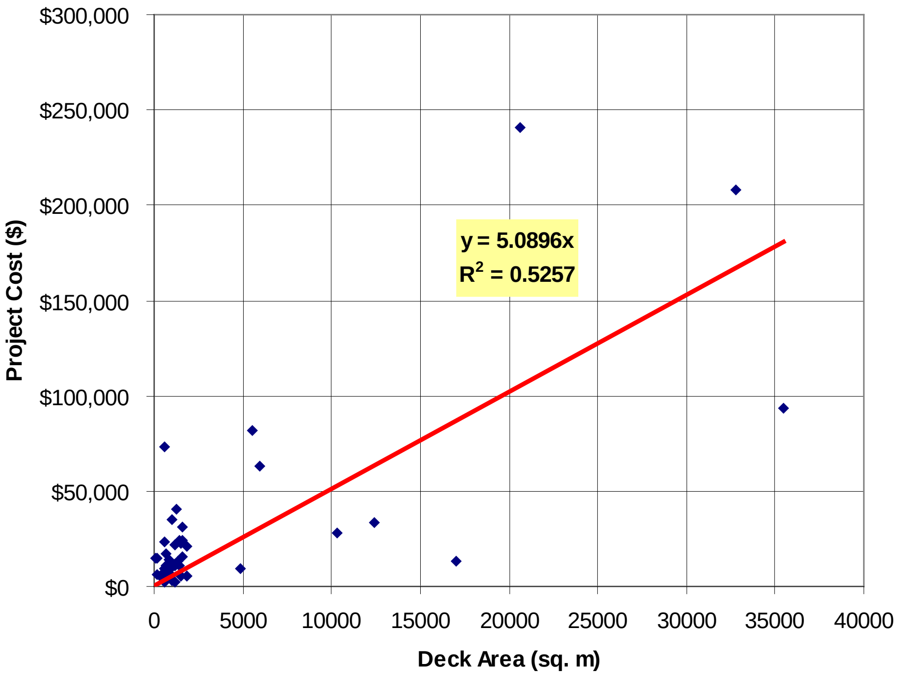


Figure 5.12. Variation in bridge joint rehabilitation project total costs relative to deck area

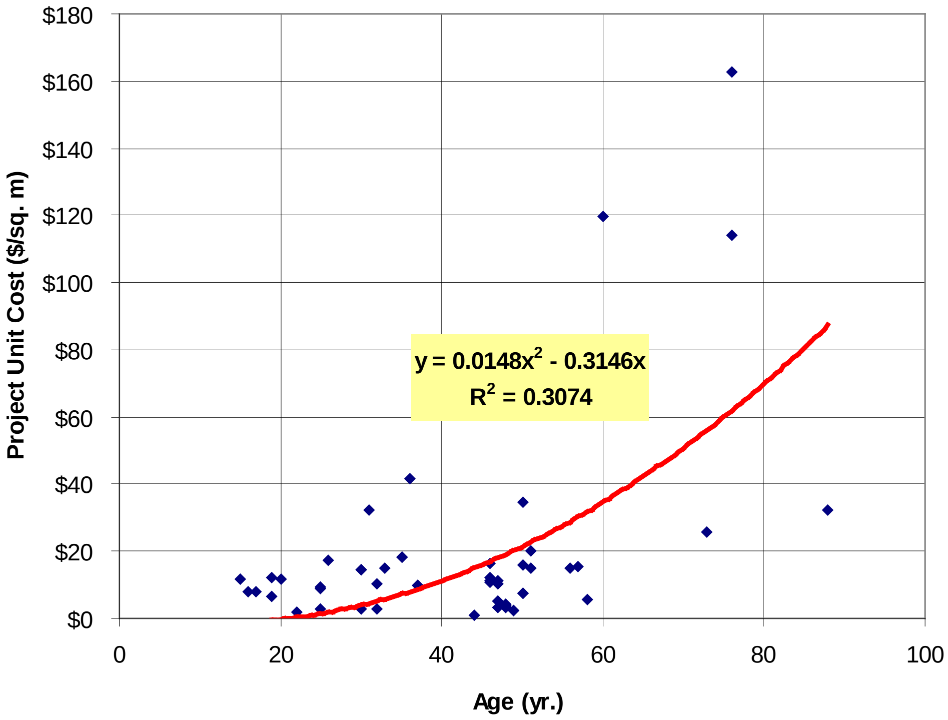


Figure 5.13. Variation in bridge joint rehabilitation project costs per deck area relative to age

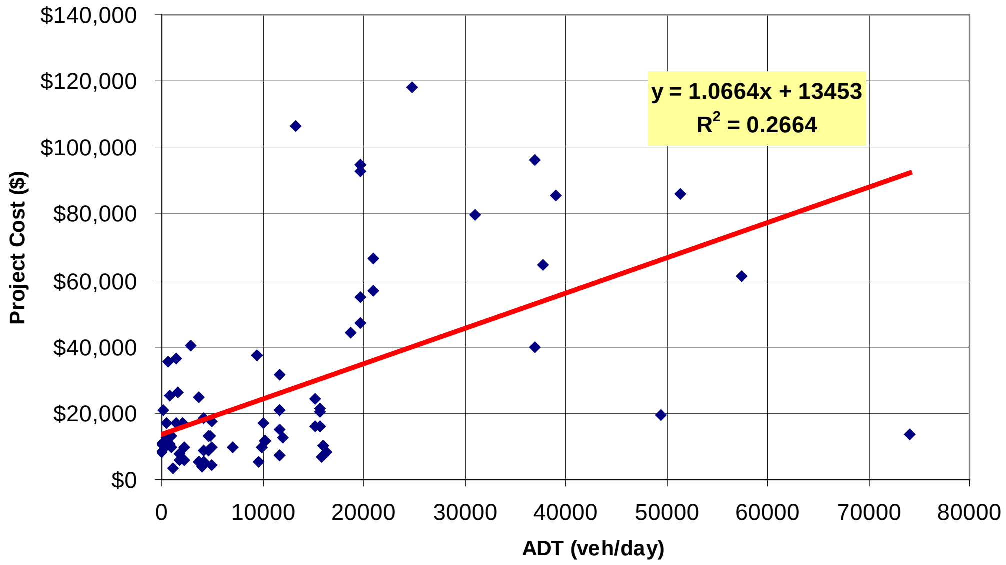


Figure 5.14. Variation in bridge minor rehabilitation project costs relative to Average Daily Traffic (ADT)

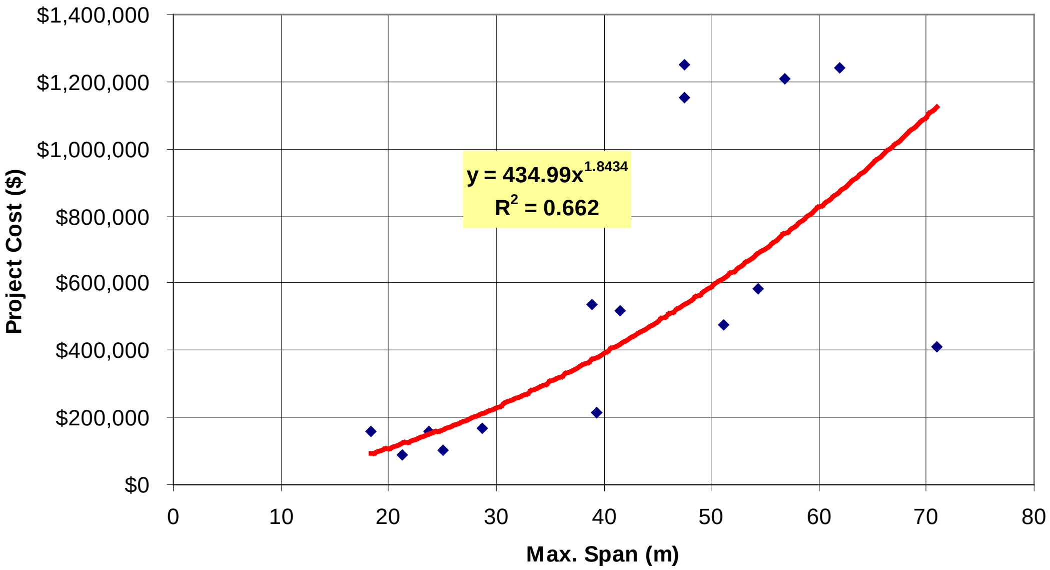


Figure 5.15. Variation in bridge painting project costs relative to maximum span

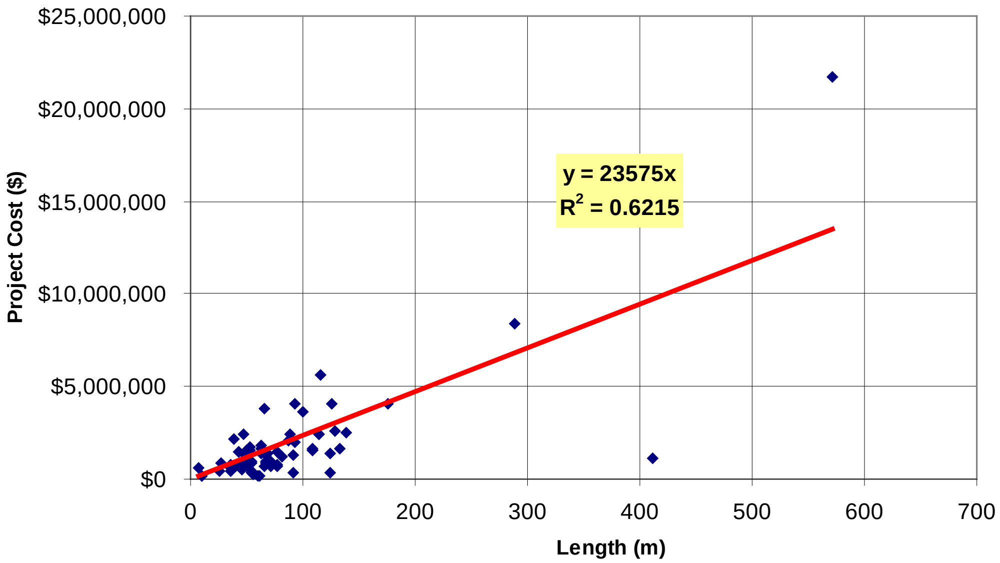


Figure 5.16. Variation in bridge widening project costs relative to bridge length

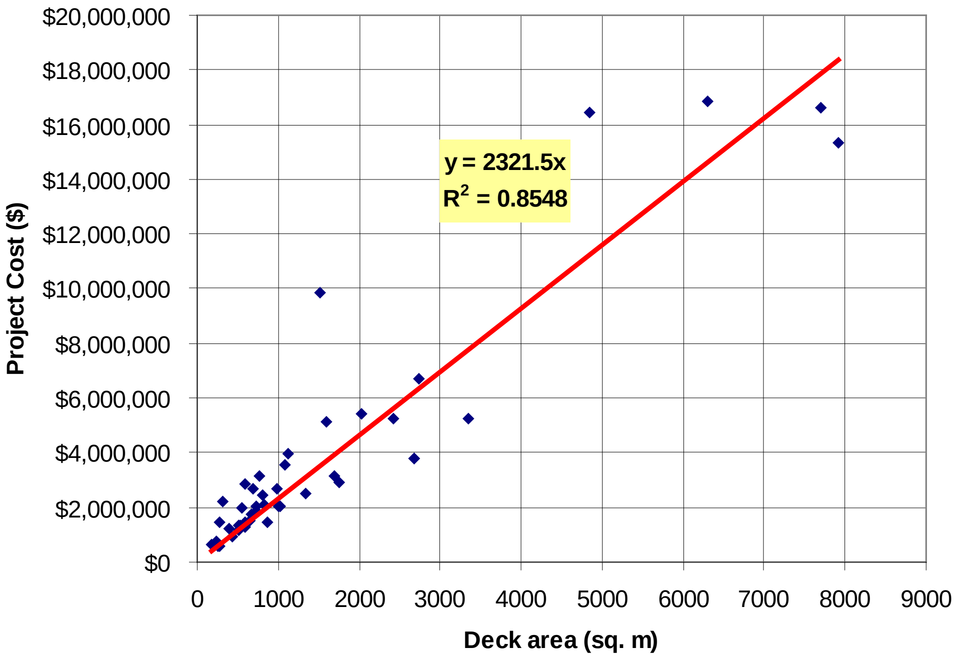


Figure 5.17. Variation in new bridge/replacement project costs relative to deck area (excl. $88m project)

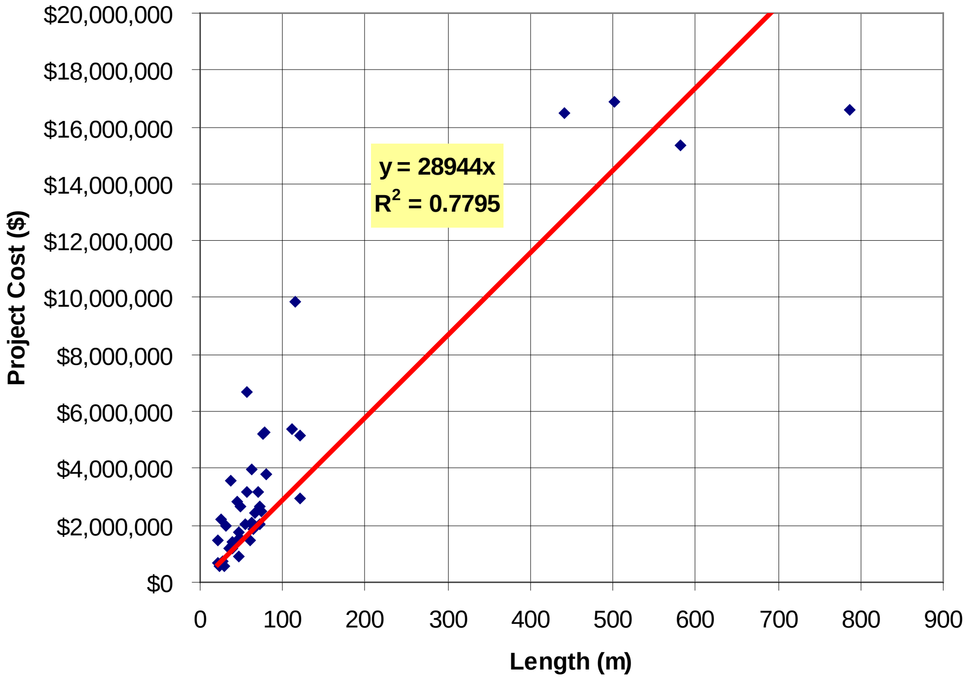


Figure 5.18. Variation in new bridge/replacement project costs relative to bridge length (excl. $88m project)

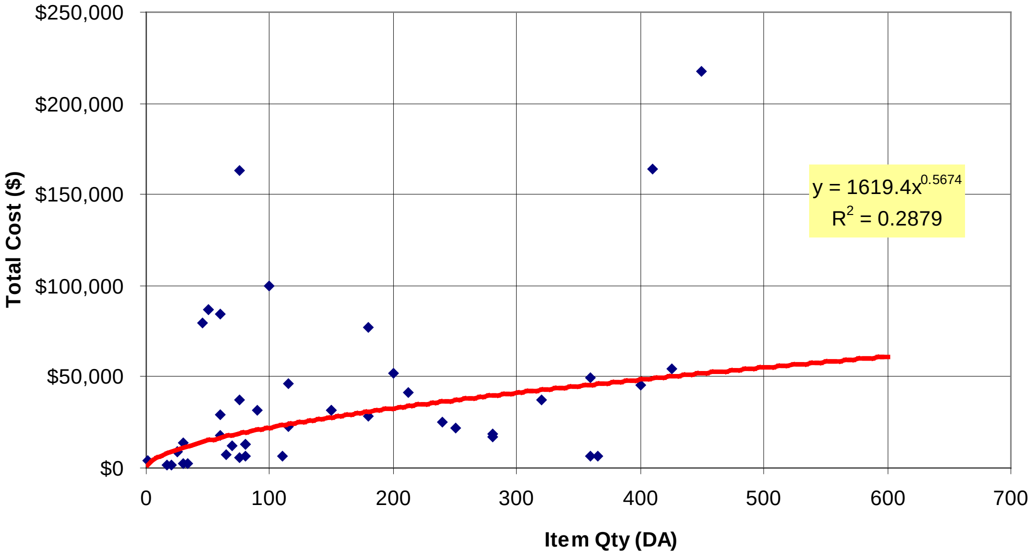


Figure 5.19. Variation in Maintenance of Traffic (MOT) total costs relative to item quantity (no. of days)

Using the age parameter as defined earlier, the various bridge ages when the projects are done, are shown as statistical distributions in Figures 5.20 to 5.24 for comparisons of project types and bid items related to bridge rehabilitation. In Figure 5.20, is seen that bridge widening appears to be done earlier than major rehabilitation projects. But for the other categories shown, it is not very clear which is done earlier, or later as shown in Figures 5.21 to 5.24; the spread of the distributions overlap in most cases.

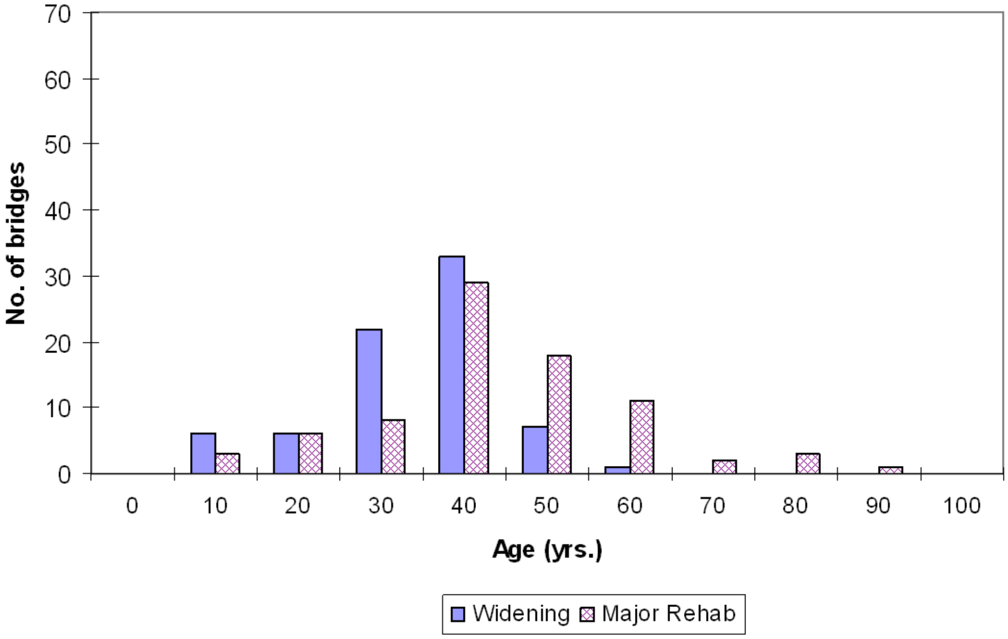


Figure 5.20. Comparison of the distributions of bridge age for bridge widening and major rehab projects

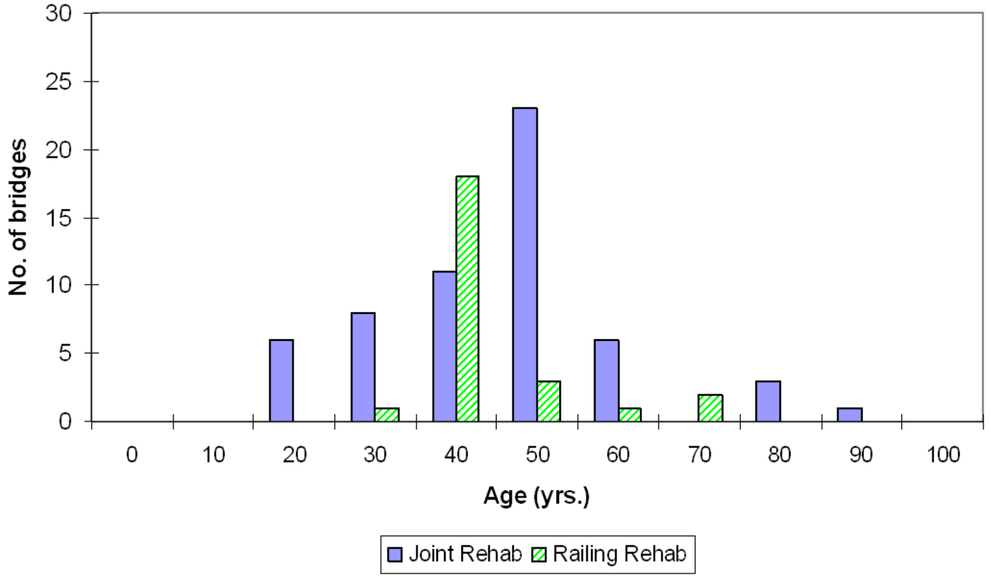


Figure 5.21. Comparison of the distributions of bridge age for joint rehabilitation and railing rehabilitation projects

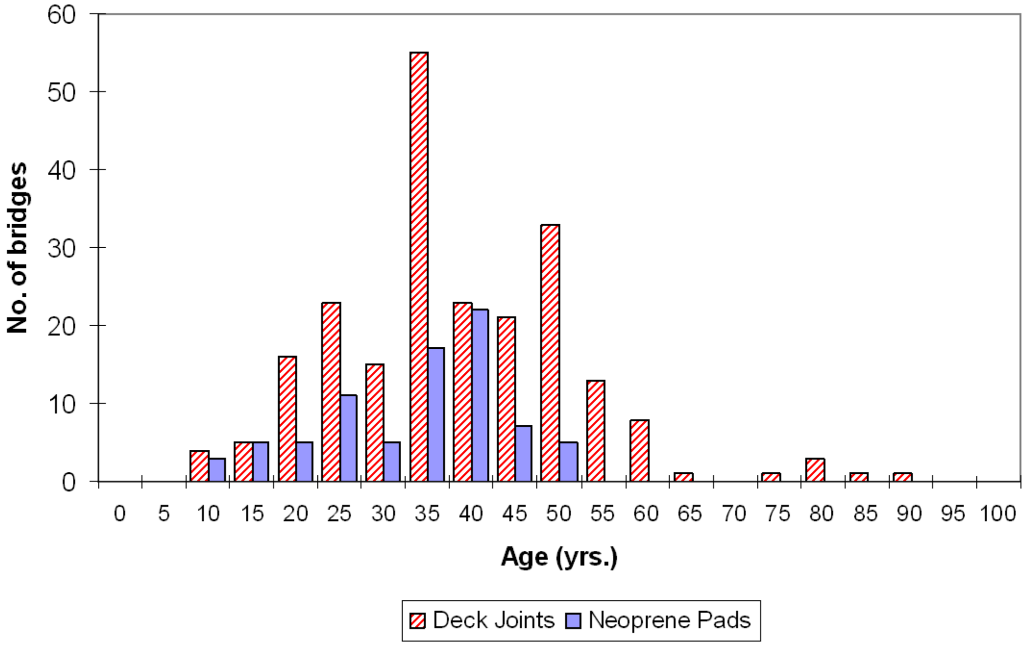


Figure 5.22. Comparison (using bid items) of the distributions of bridge age at repair: deck joints vs. neoprene pads on rehabilitation projects

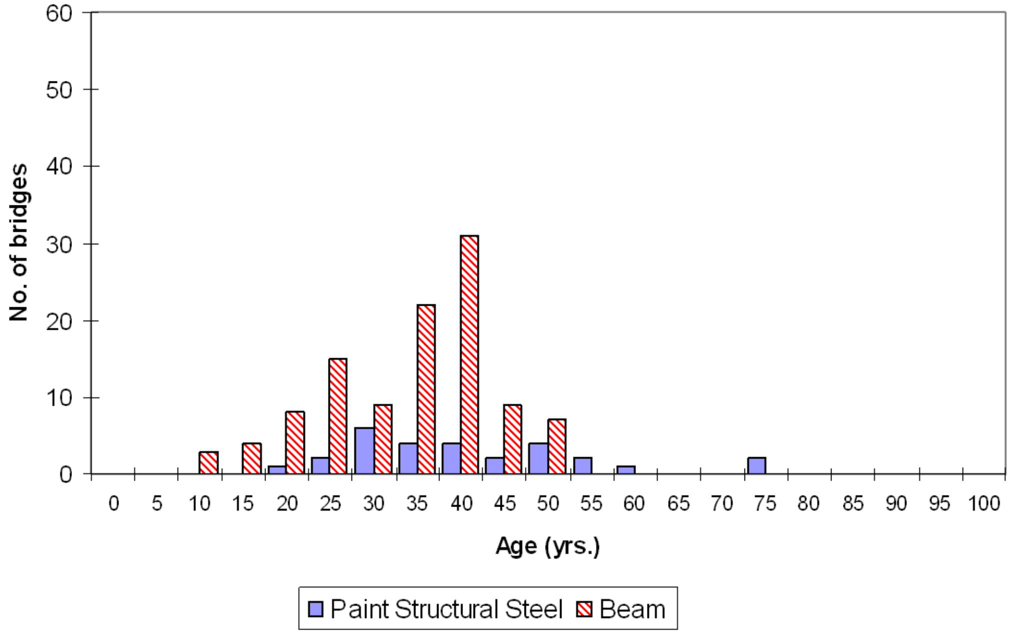


Figure 5.23. Comparison (using bid items) of the distributions of bridge age at repair: paint structural steel vs. beam repair on rehabilitation projects

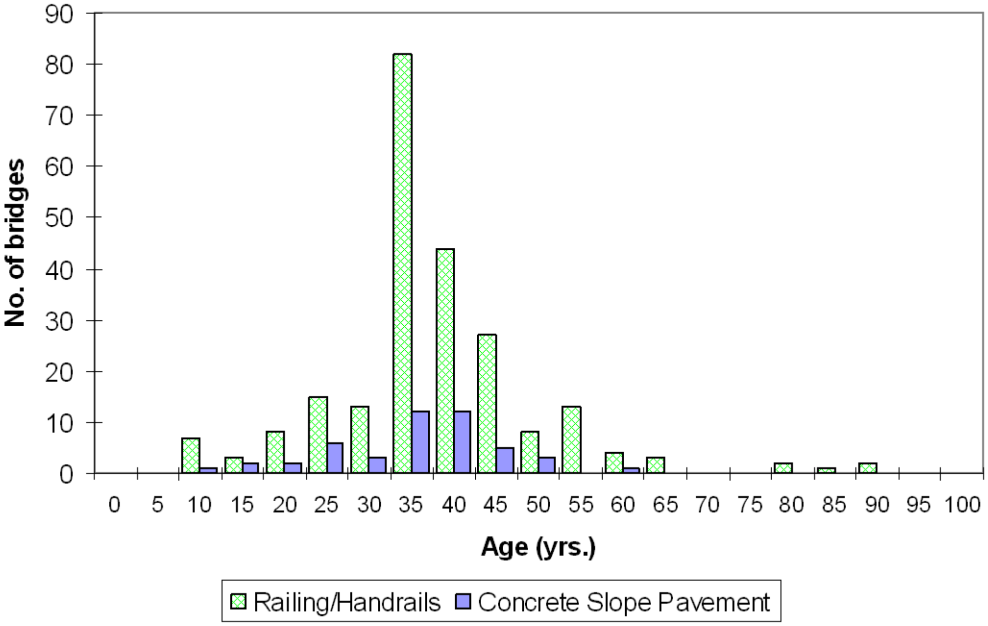


Figure 5.24. Comparison (using bid items) of the distributions of bridge age at repair: railings/handrails vs. concrete slope pavement on rehabilitation projects

In investigating the causes of variation in the MOT costs, it was necessary to consider the influence, if any, of the traffic characteristics of the roadways passing under the bridge, i.e. under roadways. The NBI inventory code identifies such roadways. An initial simple correlation analysis indicated that the only two significantly correlated traffic characteristics are the Average Daily Traffic (ADT) and the Speed limit of the under roadways. The MOT costs data has 48 bridge projects listed from the FDOT's statewide bid cost data (Table 5.7). Of these 48 bridge projects, 17 have under roadways associated with them (Table 5.8). Considering only the bridges with NBI Over_Under code of "2" only, i.e., only one roadway passes under the bridge (9 bridge projects), the variation of the MOT unit price with the under roadway ADT is as shown in Figure 5.25, while the variation with under roadway speed is shown in Figure 5.26. For all the bridge under roadway situations, i.e. including NBI Over_Under codes "2" "A" "B" "C", etc., with a total of 17 bridge projects, but excluding two records with negative ADT data, the variation of the MOT unit price with under roadway ADT and speed are shown in Figures 5.25 and 5.26 respectively. The number of data for these statistical analyses may be too low to make strong conclusions, but the trends shown on the graphs in Figures 5.25 to 5.27, confirms the general belief that MOT costs will increase with increase of traffic volume and vehicle speeds under that bridge.

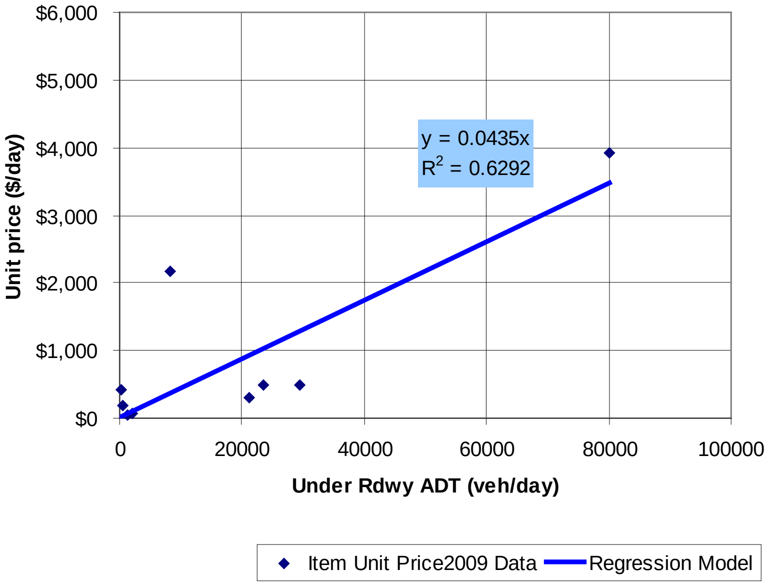


Figure 5.25. Variation in unit price of MOT Relative to under roadway ADT (single under roadways)

Table 5.8. MOT costs of bridge projects and over/under roadway characteristics

BridgeNo	TypeWork	LetDate	Item Qty	UnitPrice	Amount	NBI Over_Under Code	No. of Main Spans	Max Span (m)	Bridge Length (m)	Deck Area (sq. m)	Under Rdwy No. of Lanes	Under Rdwy ADT (veh/day)	Under Rdwy Truck Pct (%)	Under Rdwy Speed (km/h)	Under Rdwy Vert. Clr (m)	Under Rdwy Horiz. Clr (m)
700176	REHAB-SUBSTRUCTURE	3/27/2008	1	$3,917.13	$3,917.13	2	4	26.80	82.30	1058.54	4	80000	16	112	4.92	19.90
720076	CATHODIC PROTECTION	3/23/2005	60	$483.67	$29,020.00	2	6	246.89	2248.05	39792.96	2	29500	11	56	5.00	7.86
720580	MAJOR REHAB	8/30/2006	75	$2,174.72	$163,104.00	2	7	47.20	497.40	8158.00	6	8200	4	72	99.99	21.95
860230	MAJOR REHAB - MOVABLE	2/25/2005	450	$483.67	$217,650.00	2	1	33.50	391.40	7320.00	5	23500	4	56	5.82	30.70
860479	PAINTING	2/2/2007	110	$57.02	$6,272.00	2	4	41.50	132.90	1211.08	2	1200	5	56	7.01	19.69
870592	REHAB-MOVABLE	6/26/2008	180	$427.99	$77,038.79	2	1	44.50	431.65	9029.61	1	300	3	40	5.15	10.41
930053	PAINTING	10/3/2008	75	$75.69	$5,677.00	2	1	18.29	357.04	6893.03	2	2000	3	56	7.28	11.49
930154	REHAB-MOVABLE	2/29/2008	212	$194.68	$41,271.79	2	1	34.10	148.40	1583.00	2	560	5	40	6.71	7.32
930157	FENDER	2/3/2006	60	$294.49	$17,669.60	2	1	28.00	735.70	12650.00	4	21280	5	56	4.08	17.31
860512	MAJOR REHAB	8/5/2005	200	$259.66	$51,931.29	A	24	62.80	1200.60	15589.31	6	48500	20	113	5.09	99.99
870575	MAJOR REHAB	4/24/2008	100	$999.15	$99,915.20	A	7	50.30	1206.70	15204.42	2	11520	1	48	5.18	11.80
860230	MAJOR REHAB - MOVABLE	2/25/2005	450	$483.67	$217,650.00	B	1	33.50	391.40	7320.00	1	20	-1	-1	5.12	21.18
860479	PAINTING	2/2/2007	110	$57.02	$6,272.00	B	4	41.50	132.90	1211.08	1	1200	5	-1	7.28	9.30
860512	MAJOR REHAB	8/5/2005	200	$259.66	$51,931.29	B	24	62.80	1200.60	15589.31	3	26511	5	89	5.03	17.10
870575	MAJOR REHAB	4/24/2008	100	$999.15	$99,915.20	B	7	50.30	1206.70	15204.42	2	1056	3	48	4.24	11.98
870575	MAJOR REHAB	4/24/2008	100	$999.15	$99,915.20	C	7	50.30	1206.70	15204.42	2	110	1	40	5.27	7.07
860512	MAJOR REHAB	8/5/2005	200	$259.66	$51,931.29	C	24	62.80	1200.60	15589.31	2	13612	5	113	5.09	99.99

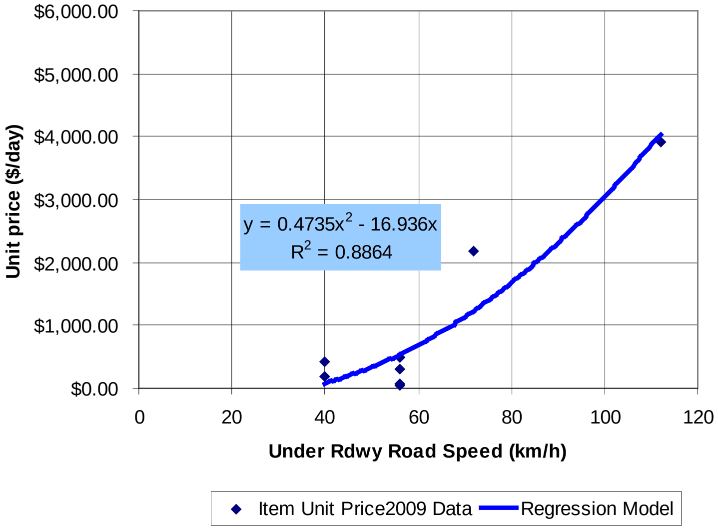


Figure 5.26. Variation in unit price of MOT relative to under roadway speed (single under roadways)

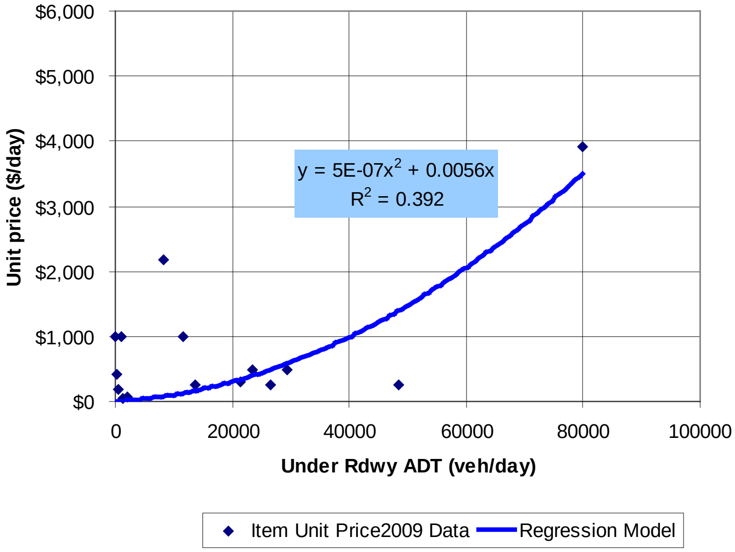


Figure 5.27. Variation in unit price of MOT relative to under roadway ADT (all under roadways)

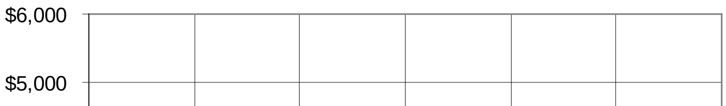


Figure 5.28. Variation in unit price of MOT relative to under roadway speed (all under roadways)

5.3 FDOT District Two Bridge Cost Data

As a preliminary study, historical cost data were first reviewed and analyzed for bridge work done at an FDOT District. The research team visited FDOT District Two Bridge Maintenance Offices in Lake City and Jacksonville, to discuss and observe the process of recording bridge maintenance costs for bridge management. Using the original scanned bid reports and summary Excel spreadsheet summary worksheets provided by the District Two personnel, the data were reviewed to develop data Excel spreadsheets, identifying the work types for the projects and also listing the individual bid items and category of work item. The data was provided in terms of two major types of bridge projects: Bridge Rehabilitation and Repair Program (BRRP) and Bridge Widening projects. The BRRP projects included 68 bid contracts, while the widening projects had 63 bid contracts. In both cases, the data provided summary information on the specific bridge(s) involved, roadway carried, the year of the bid letting, financial number, total cost, and the project scope. The year of letting ranged from 1999 to 2008 for both project types, and a few project records had to be removed because of missing data. Some projects had only the summary data provided but several had detailed bid or pay item (scanned) documents were provided, linked to each of the projects listed.

Each project record was carefully reviewed by pay item to classify the bid item costs into type of work categories: Mobilization; Maintenance of Traffic (MOT); Structures; Roadway; General; Lighting; and Signage. The project scope information was further refined with a review of the listed bid items to develop a new information of the type of work performed. The costs were adjusted to accommodate cases of multiple bridge listings for a single bid contract, by basically apportioning the costs equally to the bridges involved. The refined bridge cost data was adjusted to 2009 dollars using the method described earlier (the FDOT PDC factors), and then merged with the 2007 Pontis bridge inventory data for roadway and bridge information. The new database was then used for statistical analyses to obtain basic descriptive statistics and investigate cost relationships to bridge geometric and roadway attributes.

Tables 5.9 to 5.15 show, respectively, the summary of results for the following work types: Cathodic Protection; Fender repair and replacement; Painting; Painting and steel repairs; Scour countermeasures; and Steel repairs. Cathodic protection cost on the average of eight projects was $15.43/SF of bridge deck area while the fender projects cost about $17.88/SF from the average of 21 projects. For both cases, some outliers were observed. Excluding these outliers will result in mean estimates of $6.52/SF and $9.12/SF respectively for cathodic protection and fender projects. From 22 projects, cost of painting was estimated as $21.49/SF (or $15.78 without outliers) while painting when done together with repairs cost about $375.31/SF (or $27.35/SF without four outliers), based on 11 projects. Seven scour countermeasures projects were used to estimate the mean cost of $59.60/SF (or $68.84/SF without outliers), while steel repairs on four projects indicated an average of $20.51/SF. Table 5.14 also shows the unit costs for miscellaneous work types such as rebuild movable, repair/replace bearings, repair/replace joints, substructure (piling) repair, span lock repair, repair/replace submarine cable, replace beam, and substructure repairs.

In the BRRP projects, structures cost was observed to the predominant portion of the total costs, constituting between 67% and 91% of the total project costs. Maintenance of Traffic (MOT) costs was observed to be between 1% and 14% of the total project costs while Mobilization costs range from 3% to 13%. The bridge widening costs (structures cost only) are summarized in Table 5.16, adjusted to 2009 dollars using the FDOT PDC factors. It indicates that based on the average of 40 projects, it costs about $6,000/LF of bridge length to widen the bridge. Investigation into the relationship between costs and bridge attributes indicate some findings illustrated in Figures 5.29 to 5.32. By first estimating the correlation coefficients between costs and the various bridge and roadway attributes, simple relationships are shown for the BRRP projects in Figures 5.29 to 5.31. Similarly, for bridge widening projects, correlation coefficients acted as guides to produce the charts shown in Figure 5.32. While the shown coefficients of determination (R^2) are not perfect values, the relationships indicated cannot be ignored. For instance, for cathodic protection and fender repair/replacement, the Maintenance of Traffic (MOT) costs increase with bridge length. For painting projects, both MOT and Mobilization costs increase with length of the bridge. Bridge widening costs also increase with length of the bridge as shown in Figure 5.32. The statistical distribution for bridge widening costs is also shown in Figure 5.33, showing a left-skewed distribution.

Table 5.9. Summary of FDOT District 2 BRRP costs (adjusted to 2009 dollars) per sq. meter deck area for cathodic protection

Bridge ID	*Feature Description*	*Year*	Mobilization Cost/SM	Maintenance of Traffic Cost/SM	*Structures Cost/SM*	*Roadway Cost/SM*	*General Cost/SM*	*Lighting Cost/SM*	*Signing Cost/SM*	Total Cost/SM	Total Cost	
720076	SR10A/ST. JOHNS R.	1999	2.26	1.41	34.42	0.00	0.00	0.00	0.00	38.09	1,515,721.63	*
720044	SR10/SAN PABLO RIVER	1999	1.92	0.76	10.01	0.00	0.00	0.00	0.00	12.70	163,721.56	*
720063	SR105/ HECKSCHER DR	2000	25.70	6.41	765.19	0.00	39.57	0.00	0.00	836.86	572,216.60	* outlier
720063	SR105/ HECKSCHER DR	2001	0.00	0.00	0.00	0.00	0.00	0.00	0.00	137.11	93,753.22	
720076	SR 10A MATHEWS BR	2005	1.82	1.14	27.81	0.00	0.00	0.00	0.00	30.77	1,224,561.29	*
780089	SR 312 (EB)	2005	0.00	0.00	0.00	0.00	0.00	0.00	0.00	9.73	137,845.00	
720060	SR 105(HECKSCHER DR)	2006	0.00	0.00	0.00	0.00	0.00	0.00	0.00	93.35	293,225.65	
780089	SR 312 (EB)	2008	5.87	4.66	154.93	0.00	4.01	0.00	0.00	169.47	2,400,720.19	*
	* Costs with breakdown	Mean	7.51	2.88	198.47	0.00	8.72	0.00	0.00	217.58		
		Std. Dev.	10.30	2.51	321.95	0.00	17.34	0.00	0.00	351.75		
		%	3%	1%	91%	0%	4%	0%	0%	100%		
								(all 8 projects)	Mean	166.01	$15.43	Per SF
									Std. Dev.	277.42	$25.78	Per SF
								(w/o outlier)	Adj. Mean	70.18	$6.52	Per SF
									Adj. Std. Dev.	63.79	$5.93	Per SF

Table 5.10. Summary of FDOT District 2 BRRP costs (Adjusted to 2009 Dollars) per sq. meter deck area for Fender repair and replacement

Bridge ID	*Feature Description*	*Year*	Mobilization Cost/SM	Maintenance of Traffic Cost/SM	*Structures Cost/SM*	*Roadway Cost/SM*	*General Cost/SM*	*Lighting Cost/SM*	*Signing Cost/SM*	Total Cost/SM	Total Cost	
780074	A1A/ MATANZAS RIVER	1999	21.94	22.10	206.71	0.00	0.00	0.00	0.00	250.75	1,232,176.80	*
780099	SR A1A	2001	0.45	0.10	3.39	0.00	0.24	0.00	0.00	4.18	79,293.69	*
780056	SR 16 /SHANDS BRIDGE	2002	0.00	0.00	52.44	0.00	3.21	0.00	0.00	55.65	1,175,158.06	*
720068	BEACH BLVD/ SR 212	2003	40.71	2.30	71.93	0.00	2.97	0.00	0.00	117.92	186,773.88	*
720068	US 90 / SR 212	2003	0.00	0.00	0.00	0.00	0.00	0.00	0.00	46.76	74,064.91	
720057	SR 105/HECKSCHER DR.	2004	3.28	1.64	62.31	0.00	4.44	0.00	0.00	71.67	278,796.73	*
760044	US 17	2004	0.00	0.00	0.00	0.00	0.00	0.00	0.00	12.47	96,821.97	
720032	SR 115/LEM TURNER RD	2005	30.21	7.21	216.10	0.00	14.47	0.00	0.00	267.99	707,855.84	*
720076	SR-10A(MATHEWS)	2005	1.71	2.88	14.19	0.00	0.94	0.00	0.00	19.73	785,298.16	*
720052	SR 15(US 17)	2006	20.95	8.18	145.72	0.00	5.23	7.77	0.00	187.85	1,220,935.38	*
720005	SR 211	2006	66.26	25.87	460.95	0.00	16.54	24.57	0.00	594.19	2,441,870.76	* outlier
720629	SR 9/I-95 @ 8TH ST	2006	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.71	89,979.04	
720061	SR 105(HECKSCHER DR)	2008	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1,580.04	4,077,826.57	outlier
720571	SR 13-NB ACOSTA BR	2008	0.00	0.00	0.00	0.00	0.00	0.00	0.00	15.54	179,166.12	
720069	BEACH BLVD/ SR 212	2003	40.71	2.30	71.93	0.00	2.97	0.00	0.00	117.92	186,773.88	*
720068	US 90 / SR 212	2003	0.00	0.00	0.00	0.00	0.00	0.00	0.00	46.76	74,064.91	
720059	SR 105/HECKSCHER DR.	2004	4.63	2.31	87.96	0.00	6.26	0.00	0.00	101.17	278,796.73	*
720060	SR 105/HECKSCHER DR.	2004	4.06	2.03	77.17	0.00	5.50	0.00	0.00	88.75	278,796.73	*
760045	US 17	2004	0.00	0.00	0.00	0.00	0.00	0.00	0.00	12.47	96,821.97	
720272	SR 115/LEM TURNER RD	2005	30.50	7.28	218.16	0.00	14.61	0.00	0.00	270.55	707,855.84	*
720053	SR 15(US 17)	2006	19.45	7.59	135.31	0.00	4.85	7.21	0.00	174.42	1,220,935.38	*
	* Costs with breakdown	Mean	20.35	6.56	130.31	0.00	5.87	2.83	0.00	165.91		
		Std. Dev.	19.81	7.92	118.39	0.00	5.42	6.82	0.00	150.86		
		%	12%	4%	79%	0%	4%	2%	0%	100%		
	(w/o outlier)	Adj. Mean	16.82	5.07	104.87	0.00	5.05	1.15	0.00	132.97		
		Adj. Std. Dev.	12.55	2.98	88.38	0.00	5.94	0.00	0.00	100.87		
		%	13%	4%	79%	0%	4%	1%	0%	100%		
								(all 21 projects)	Mean	192.36	$17.88	Per SF
									Std. Dev.	346.82	$32.23	Per SF
								(w/o 2 outliers)	Adj. Mean	98.17	$9.12	Per SF
									Adj. Std. Dev.	91.28	$8.48	Per SF

Table 5.11. Summary of FDOT District 2 BRRP (Adjusted to 2009 Dollars) costs per sq. meter deck area for Painting

Bridge ID	*Feature Description*	*Year*	Mobilization Cost/SM	Maintenance of Traffic Cost/SM	*Structures Cost/SM*	*Roadway Cost/SM*	*General Cost/SM*	*Lighting Cost/SM*	*Signing Cost/SM*	Total Cost/SM	Total Cost	
720027	SR 13/GOODBYS LAKE	1999	9.16	6.37	129.33	0.00	0.00	0.00	0.00	144.86	241,406.65	*
720072	SR-105/SIMPSON CREEK	1999	26.76	25.71	239.86	0.00	0.00	0.00	0.00	292.32	78,485.20	*
720023	SR-105/I-95	1999	18.73	11.80	79.14	0.00	0.00	0.00	0.00	109.67	82,010.21	*
720056	SR-105/BROWARD R.	1999	9.56	2.70	83.53	0.00	0.00	0.00	0.00	95.80	176,313.32	*
320017	SR6/WITHLACOOCHEE OF	1999	6.38	9.90	105.48	0.00	0.00	0.00	0.00	121.76	171,422.81	*
740018	US 1/SR 15 ST.MARYS	1999	3.71	5.11	133.53	0.00	5.64	0.00	0.00	147.98	179,136.63	*
720163	I-95/ MYRTLE AVE.	1999	7.74	3.50	146.08	0.00	0.00	0.00	0.00	157.32	1,825,070.95	*
720081	SR 10A/ MATHEWS EXPY	2000	33.87	32.17	121.92	0.00	8.81	0.00	0.00	196.76	204,163.40	*
260006	US 27/SANTA FE RIVER	2001	29.05	22.94	447.80	0.00	18.40	0.00	0.00	518.18	366,542.30	*
720087	SR 152/BAYMEADOWS RD	2001	1.45	1.21	13.59	0.00	1.06	0.00	0.00	17.31	98,126.18	*
720076	SR10A/ST.JOHNS RIVER	2001	0.00	0.00	0.00	0.00	0.00	0.00	0.00	124.48	4,953,420.28	
720518	SR 9A/ST.JOHNS RIVER	2001	0.92	0.51	48.09	0.00	9.48	0.00	0.00	59.00	5,488,594.08	*
320016	SR 6	2003	14.60	7.48	113.06	0.00	10.71	0.00	0.00	145.85	199,889.96	*
350030	SR 6	2003	26.65	13.66	206.39	0.00	19.55	0.00	0.00	266.25	199,889.96	*
330009	SR 51 (HAL ADAMS)	2005	2.92	1.32	129.01	0.00	9.19	0.00	0.00	142.44	265,502.89	*
720126	SR 9A OVER US 17 &	2006	10.19	6.04	151.80	0.00	15.29	0.00	0.00	183.32	244,494.62	*
720518	SR 9A(DAMES POINT)	2007	14.85	2.23	130.27	0.00	1.17	0.00	0.00	148.52	13,816,475.90	*
740031	US 1/SR 15 ST.MARYS	1999	3.71	5.11	133.53	0.00	5.64	0.00	0.00	147.98	179,136.63	*
370004	SR 51 (HAL ADAMS)	2005	3.96	1.79	175.08	0.00	12.47	0.00	0.00	193.31	265,502.89	*
370005	SR 51 (HAL ADAMS)	2005	14.87	6.74	657.12	0.00	46.81	0.00	0.00	725.53	265,502.89	* outlier
370006	SR 51 (HAL ADAMS)	2005	19.79	8.97	874.75	0.00	62.31	0.00	0.00	965.82	265,502.89	* outlier
720286	SR 9A OVER US 17 &	2006	10.19	6.04	151.80	0.00	15.29	0.00	0.00	183.32	244,494.62	*
	* Costs with breakdown	Mean	12.81	8.63	203.39	0.00	11.51	0.00	0.00	236.35		
		Std. Dev.	9.76	8.54	208.27	0.00	15.91	0.00	0.00	228.83		
		%	5%	4%	86%	0%	5%	0%	0%	100%		
	(w/o outliers > $700/SM)	Adj. Mean	12.34	8.72	144.17	0.00	6.98	0.00	0.00	172.21		
		Adj. Std. Dev.	10.13	8.99	89.54	0.00	6.87	0.00	0.00	104.79		
		%	7%	5%	84%	0%	4%	0%	0%	100%		
							(all 22 projects)		Mean	231.26	$21.49	Per SF
									Std. Dev.	224.58	$20.87	Per SF
							(w/o 2 outliers)		Adj. Mean	169.82	$15.78	Per SF
									Adj. Std. Dev.	102.55	$9.53	Per SF

Table 5.12. Summary of FDOT District 2 BRRP costs (Adjusted to 2009 Dollars) per sq. meter deck area for painting and steel repairs

Bridge ID	*Feature Description*	*Year*	Mobilization Cost/SM	Maintenance of Traffic Cost/SM	*Structures Cost/SM*	*Roadway Cost/SM*	*General Cost/SM*	*Lighting Cost/SM*	*Signing Cost/SM*	Total Cost/SM	Total Cost	
780090	SR206/CWW	2000	10.10	5.18	65.22	0.00	3.27	0.00	0.00	83.77	991,148.42	
780056	SR 16/ST JOHN RIVER	2000	6.24	14.09	10.53	0.00	2.35	0.00	0.00	33.21	701,397.91	
720107	SR 228 HART BRIDGE	2002	9.61	33.48	30.43	0.00	3.56	0.00	0.00	77.08	1,797,537.42	
720022	SR 5 (MAIN STREET)	2003	24.86	11.52	217.79	0.00	1.78	0.00	0.53	256.48	2,311,624.18	
720071	SR 105	2004	28.51	4.56	354.54	0.00	25.14	0.00	0.00	412.76	110,820.98	
740008	US-17(SR-5)	2004	194.20	197.67	4,529.40	117.92	66.63	0.00	12.09	5,117.91	5,879,657.09	outlier
720375	SR 5 (MAIN STREET)	2003	234.65	108.78	2,055.70	0.00	16.76	0.00	5.02	2,420.91	2,311,624.18	outlier
720376	SR 5 (MAIN STREET)	2003	1,741.31	807.25	15,255.17	0.00	124.38	0.00	37.27	17,965.39	2,311,624.18	outlier
720377	SR 5 (MAIN STREET)	2003	1,633.95	757.49	14,314.66	0.00	116.71	0.00	34.98	16,857.79	2,311,624.18	outlier
720378	SR 5 (MAIN STREET)	2003	75.97	35.22	665.55	0.00	5.43	0.00	1.63	783.79	2,311,624.18	
720072	SR 105	2004	28.51	4.56	354.54	0.00	25.14	0.00	0.00	412.76	110,820.98	
		Mean	362.54	179.98	3,441.23	10.72	35.56	0.00	8.32	4,038.35	$375.31	Per SF
		Std. Dev.	660.09	303.77	5,769.36	35.55	46.08	0.00	14.23	6,787.03	$630.76	Per SF
		%	9%	4%	85%	0%	1%	0%	0%	100%		
	(w/o outliers > $1,000/SM)	Adj. Mean	26.26	15.52	242.66	0.00	9.52	0.00	0.31	294.26	$27.35	Per SF
		Adj. Std. Dev.	23.88	13.39	236.26	0.00	10.73	0.00	0.61	267.32	$24.84	Per SF
		%	9%	5%	82%	0%	3%	0%	0%	100%		
	cost of outlier projects	Mean	951.03	467.80	9,038.73	29.48	81.12	0.00	22.34	10,590.50	$984.25	Per SF
		Std. Dev.	851.84	365.61	6,722.51	58.96	49.97	0.00	16.20	7,965.74	$740.31	Per SF
		%	9%	4%	85%	0%	1%	0%	0%	100%		

Table 5.13. Summary of FDOT District 2 BRRP costs (Adjusted to 2009 Dollars) per sq. meter deck area for scour countermeasures

Bridge ID	*Feature Description*	*Year*	Mobilization Cost/SM	Maintenance of Traffic Cost/SM	*Structures Cost/SM*	*Roadway Cost/SM*	*General Cost/SM*	*Lighting Cost/SM*	*Signing Cost/SM*	Total Cost/SM	Total Cost	
740018	US 1/SR 15	1999	163.02	174.69	664.57	0.00	37.83	0.00	0.00	1,040.12	1,259,091.86	*
720218	I-95/NASSAU RIVER	1999	29.01	45.56	259.09	0.00	15.83	0.00	0.00	349.49	1,189,916.23	*
720440	SR134/TIMUQUANA RD	2000	58.84	25.40	404.98	99.17	0.00	0.00	0.00	588.39	938,238.00	
720022	SR5/ST. JOHNS RIVER	2002	0.00	0.00	0.00	0.00	0.00	0.00	0.00	44.18	398,223.69	* outlier
740031	US 1/SR 15	1999	163.02	174.69	664.57	0.00	37.83	0.00	0.00	1,040.12	1,259,091.86	*
720336	I-95/NASSAU RIVER	1999	29.01	45.56	259.09	0.00	15.83	0.00	0.00	349.49	1,189,916.23	*
720062	BRIDGE SCOUR M.SYS	2002	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1,077.00	398,223.69	
	* Costs with breakdown	Mean	88.58	93.18	450.46	19.83	21.46	0.00	0.00	673.52		
		Std. Dev.	69.04	74.86	204.33	44.35	16.28	0.00	0.00	348.58		
		%	13%	14%	67%	3%	3%	0%	0%	100%		
								(all 7 projects)	Mean	641.26	$59.60	Per SF
									Std. Dev.	415.85	$38.65	Per SF
								(w/o outlier)	Adj. Mean	740.77	$68.84	Per SF
									Adj. Std. Dev.	352.61	$32.77	Per SF

Table 5.14. Summary of FDOT District 2 BRRP costs (Adjusted to 2009 Dollars) per sq. meter deck area for steel repairs

Bridge ID	*Feature Description*	*Year*	Mobilization Cost/SM	Maintenance of Traffic Cost/SM	*Structures Cost/SM*	*Roadway Cost/SM*	*General Cost/SM*	*Lighting Cost/SM*	*Signing Cost/SM*	Total Cost/SM	Total Cost	
720022	SR5/ST. JOHNS RIVER	1999	18.93	20.27	195.87	0.00	9.41	0.00	0.00	244.49	2,203,566.63	
720076	SR-10A/ST JOHNS R.	1999	13.54	23.49	91.01	0.00	5.84	0.00	0.00	133.88	5,327,610.74	
720107	SR228/ST. JOHNS RVR	2001	9.54	33.42	49.41	0.00	3.55	0.00	0.00	95.92	2,236,910.54	
720076	MATHEWS BRIDGE	2007	37.83	17.88	346.31	1.77	4.73	0.00	0.00	408.52	16,256,173.27	
		Mean	19.96	23.77	170.65	0.44	5.88	0.00	0.00	220.70		
		Std. Dev.	12.52	6.83	132.33	0.89	2.53	0.00	0.00	140.18		
		%	9%	11%	77%	0%	3%	0%	0%	100%		
									Mean	220.70	$20.51	Per SF
									Std. Dev.	140.18	$13.03	Per SF

Table 5.15. Summary of FDOT District 2 BRRP costs (Adjusted to 2009 Dollars) per sq. meter deck area for miscellaneous work types

Bridge ID	*Feature Description*	*Year*	Mobilization Cost/SM	Maintenance of Traffic Cost/SM	*Structures Cost/SM*	*Roadway Cost/SM*	*General Cost/SM*	*Lighting Cost/SM*	*Signing Cost/SM*	Total Cost/SM	Total Cost
a. Rebuild moveable											
780090	SR-206/INTRACOASTAL	1999	3.95	8.04	33.39	0.00	0.00	0.00	0.00	45.37	536,869.30
720061	SR105/HECKSCHER DR	2000	46.70	85.28	261.82	0.00	22.47	0.00	0.00	416.27	1,074,327.93
b. Repair/replace Bearings											
720011	US 17/MAIN STREET	1999	6.29	2.15	0.57	0.00	4.77	0.00	0.00	13.78	129,778.96
720153	I-95/SO.HAMPTON AND	2002	1.27	0.91	2.81	0.00	0.25	0.00	0.00	5.24	102,814.46
c. Repair/replace joint											
760043	US 17/ST. JOHN RIVER	2002	0.00	0.00	0.00	0.00	0.00	0.00	0.00	10.65	369,731.23
720518	SR 9A/ DAMES POINT @	2007	0.80	0.79	6.21	0.00	0.28	0.00	0.00	8.08	751,305.54
d. Substructure (piling) repairs											
710022	SR 16	1999	104.07	114.32	849.59	0.00	57.42	0.00	0.00	1,125.40	1,126,451.20
780074	BRIDGE OF LIONS	1999	0.00	0.00	0.00	0.00	0.00	0.00	0.00	242.36	1,190,936.58
e. Span lock repair											
720068	US90/SR212 ICWW	2000	6.66	3.74	188.02	0.00	5.77	0.00	0.00	204.18	323,418.02
720069	US90/SR212 ICWW	2000	6.66	3.74	188.02	0.00	5.77	0.00	0.00	204.18	323,418.02
f. Repair/replace submarine cable											
780074	SRA1A/BRIDGE OF LION	2001	12.72	1.85	106.11	0.00	6.10	0.00	0.00	126.77	622,971.56
g. Replace beam											
720299	I 95 NB	2005	0.00	0.00	0.00	0.00	0.00	0.00	0.00	15.91	13,762.74
h. Superstructure repairs											
720079	SR-10A @ PALMETTO ST	2005	0.00	0.00	0.00	0.00	0.00	0.00	0.00	126.18	114,763.94

Table 5.16. Summary of FDOT District 2 bridge widening project costs (Adjusted to 2009 Dollars)

Bridge No.	Feature Description	Year	Structures Cost	Age at Widening	No. of Spans	Max Span (m)	Length (m)	Deck Area (SM)	Deck Width (m)	Bridge Main Material	Cost per Deck Area ($/SM)	Cost per Length ($/M)	
270006	SR-121/Turkey Creek	2002	1,659,727.97	32	4	13.40	53.49	1,458.30	27.26	5	1,138.13	31,027.59	
280023	SR-100/Alligator Creek	2000	1,137,200.27	46	8	4.60	36.60	625.98	17.10	1	1,816.67	31,071.05	
340001	SR-24/Back Bayou Creek	1999	192,147.19	32	1	12.20	12.50	148.55	11.89	5	1,293.47	15,371.78	
340048	US-Alt-27/Little Waccasassa River	2002	457,211.46	40	3	10.10	30.20	391.21	12.95	1	1,168.70	15,139.45	
720034	US-1/Boulevard St.	1999	448,293.92	38	3	21.90	41.80	1,007.07	24.10	5	445.15	10,724.74	
720035	US-1/Pearl St.	1999	447,500.74	38	3	19.80	42.70	1,364.37	31.95	5	327.99	10,480.11	
720036	US-Alt-1/US-17	1999	192,147.19	38	3	22.90	45.10	1,421.00	31.50	5	135.22	4,260.47	
720054	US-Alt-1/Liberty St.	1999	442,662.79	38	3	19.50	43.00	1,195.66	27.80	5	370.22	10,294.48	
720055	US-Alt-1/CSXRR	1999	1,914,205.68	38	7	24.10	138.10	4,364.30	31.60	5	438.61	13,861.01	
720083	US-Alt-1/Phoenix Ave	1999	460,318.72	38	3	19.50	41.50	996.29	24.00	5	462.03	11,092.02	
720096	US-Alt-1/17th St. & CSXRR	1999	838,485.62	37	5	17.70	67.40	1,785.78	26.50	5	469.53	12,440.44	
720097	US-Alt-1/8th St. & CSXRR	1999	2,018,130.49	37	11	24.10	237.40	5,436.59	22.90	5	371.21	8,500.97	
720126	SR-9A NB/US-17 & CSXRR	2007	2,118,373.68	37	4	39.30	86.60	1,333.72	15.40	3	1,588.32	24,461.59	
720130	SR-202/Mill Dam Branch	2005	1,055,541.63	33	7	7.90	54.30	1,170.00	20.70	2	902.17	19,439.07	
720164	I-95/Adams St.	2004	852,238.07	45	3	25.90	54.30	1,167.79	21.50	5	729.79	15,694.99	
720181	I-95 SB/Moncrief Creek	2004	738,842.23	45	3	16.20	48.50	863.16	17.80	5	855.97	15,233.86	
720182	I-95 SB/Lem Turner Rd	2004	793,578.85	45	4	17.10	59.70	776.21	13.00	5	1,022.38	13,292.78	
720195	I-10/CSCRR	2004	2,083,465.02	44	3	20.70	49.10	2,755.41	56.11	5	756.14	42,433.10	
720196	I-10EB/Stockton St	2004	2,351,280.84	44	4	15.50	56.70	2,642.00	46.60	5	889.96	41,468.80	
720207	I-10 WB/Cahoon Rd	2008	3,071,268.38	48	3	17.7	40.5	530.662	13.1	5	5,787.62	75,833.79	
720290	SR-202/St. Johns Bluff Road	2005	1,437,046.60	33	4	23.20	67.10	865.39	12.90	5	1,660.57	21,416.49	
720304	I-95 NB/Moncrief Creek	2004	651,734.30	45	3	16.20	48.50	863.16	17.80	5	755.05	13,437.82	
720305	I-95 NB/Lenm Turner Rd.	2004	588,532.93	45	4	17.10	59.70	1,062.90	17.80	5	553.70	9,858.17	
720306	I-95/Edgewood Ave	2004	1,603,608.86	45	4	14.30	51.20	527.41	10.30	5	3,040.54	31,320.49	
720326	SR-21 NB/Cedar River	2001	1,132,163.90	34	20	10.10	201.20	3,330.57	16.55	5	339.93	5,627.06	
720381	I-10 EB/Cahoon Rd	2008	3,071,268.38	48	3	17.7	40.5	530.662	13.1	5	5,787.62	75,833.79	
720416	SR-202/Equipment Crossing	2005	337,085.44	33	1	7.00	7.30	201.13	27.50	1	1,675.92	46,176.09	
720448	SR-202/Buckhead Branch	2005	1,734,564.07	27	7	7.90	54.30	706.06	13.00	2	2,456.67	31,944.09	
720449	SR-202/Ryals Swamp	2007	509,691.13	29	3	15.20	45.70	772.21	16.90	5	660.04	11,152.98	
720450	SR-202/Ryals Swamp	2007	507,496.81	29	3	15.20	45.70	932.10	20.40	5	544.47	11,104.96	
720451	SR-202/Cedar Samp Creek	2007	742,066.36	28	5	16.20	77.10	1,295.53	16.80	5	572.79	9,624.73	
720452	SR-202/Cedar Samp Creek	2007	656,615.57	28	5	16.20	77.10	1,002.52	13.00	5	654.97	8,516.41	
720458	SR-202/Equipment Crossing	2007	157,951.05	28	1	9.80	10.10	131.18	13.00	1	1,204.09	15,638.72	
720459	SR-202/Equipment Crossing	2007	143,831.52	28	1	9.80	10.10	167.50	16.60	1	858.68	14,240.74	
720460	SR-202/Hodges Blvd	2007	755,735.81	28	3	27.10	49.70	646.23	13.00	5	1,169.45	15,205.95	
720461	SR-202/Hodges Blvd	2007	715,620.86	28	3	27.10	49.70	646.23	13.00	5	1,107.37	14,398.81	
720605	SR-9A SB/Deerwood Park Blvd	2005	464,748.19	8	1	42.61	42.67	758.37	17.77	5	612.83	10,891.17	
720613	SR-202/Kernan Blvd	2007	431,738.06	12	2	27.40	54.90	988.21	18.00	5	436.89	7,864.08	
720614	SR-202/Kernan Blvd	2007	381,848.30	12	2	27.40	54.90	988.21	18.00	5	386.40	6,955.34	
780071	SR-A1A/Hospital Creek	1999	720,645.25	43	8	10.10	80.50	1,127.00	14.00	1	639.44	8,952.11	
		Mean	1,000,415.35								1,152.17	19,807.05	$6,038.74
		Stdev	772,816.71								1,229.94	16,605.99	$5,062.80
		COV	0.77								1.07	0.84	

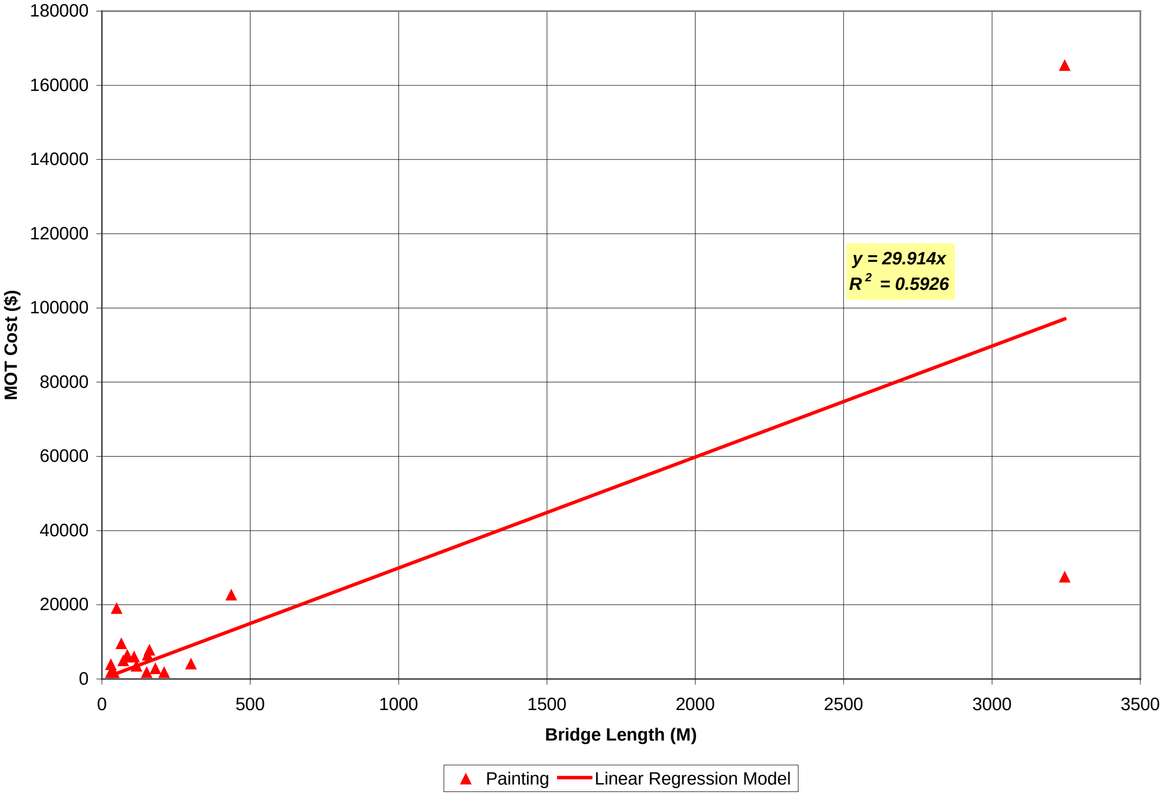


Figure 5.29. Variation of MOT costs relative to bridge overall length on FDOT District 2 BRRP painting projects

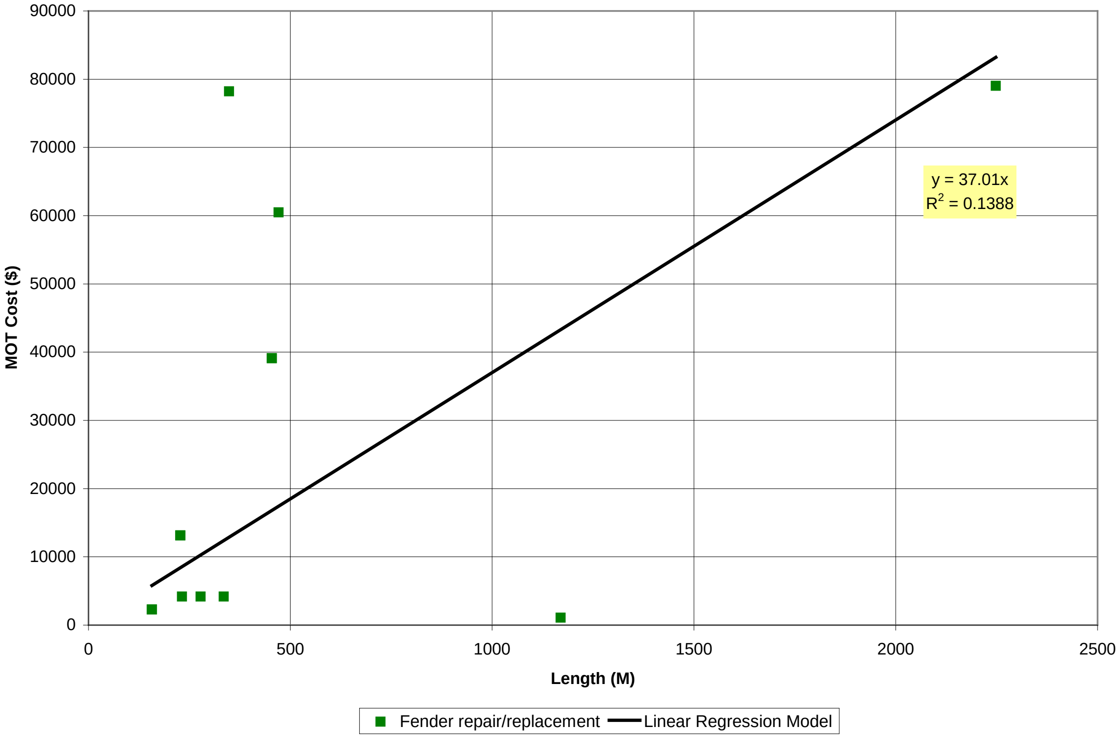


Figure 5.30. Variation of MOT costs relative to bridge overall length on FDOT District 2 BRRP fender repair and replacement projects

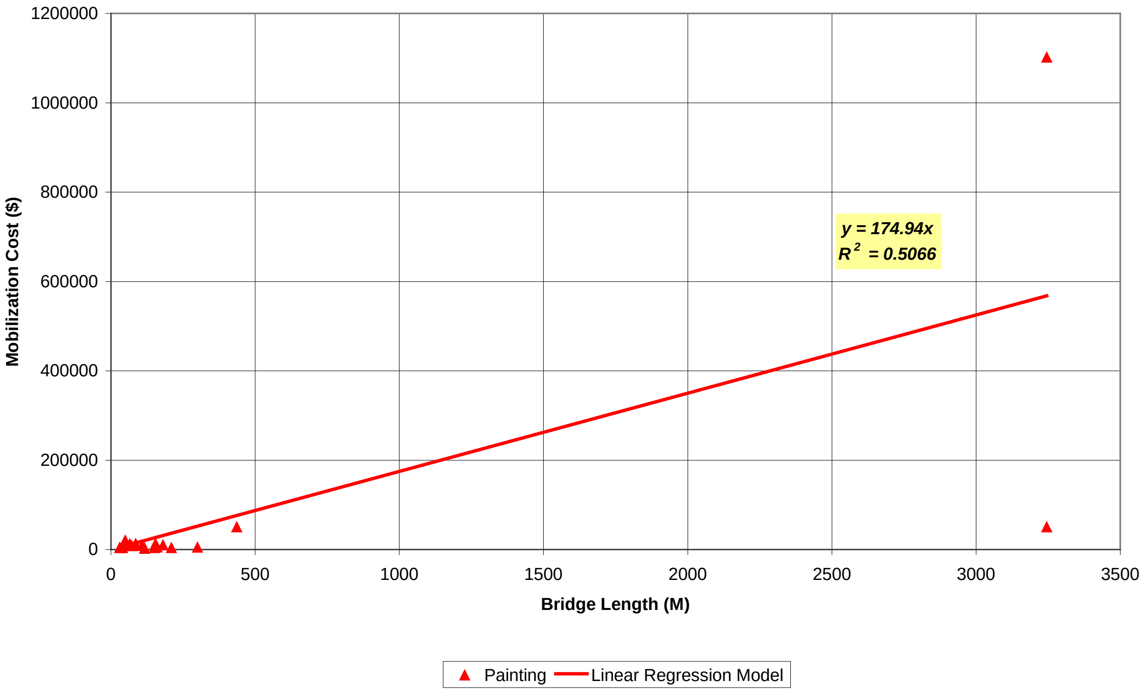


Figure 5.31. Variation of mobilization costs relative to overall bridge length on FDOT BRRP District 2 painting projects

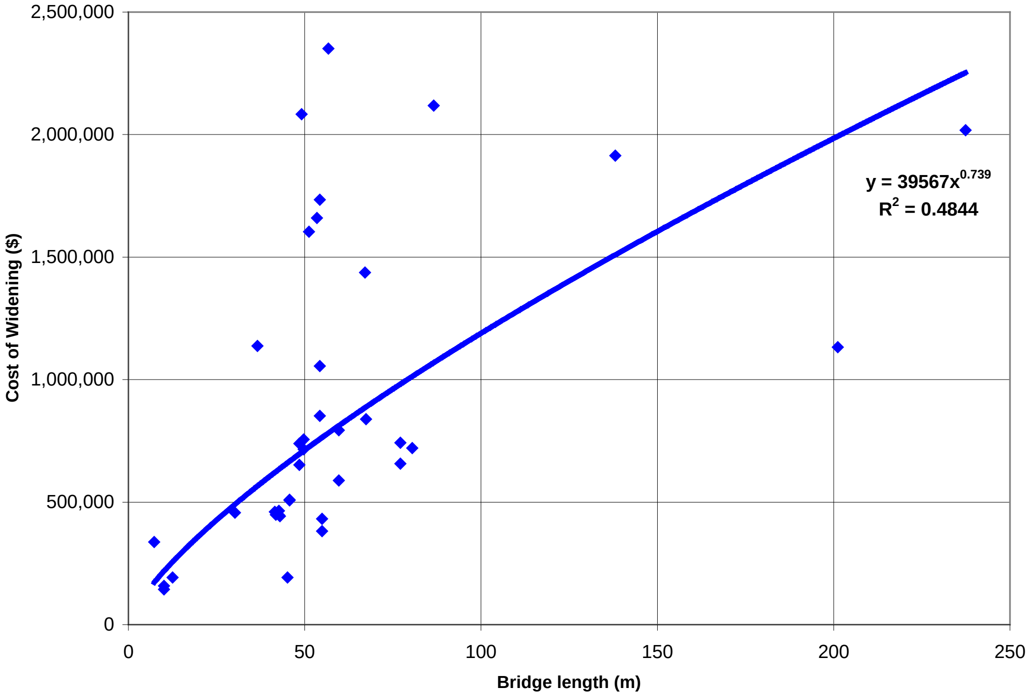


Figure 5.32. Variation of structures cost of widening relative to bridge overall length on FDOT District 2 projects (excluding $3 million outlier project)

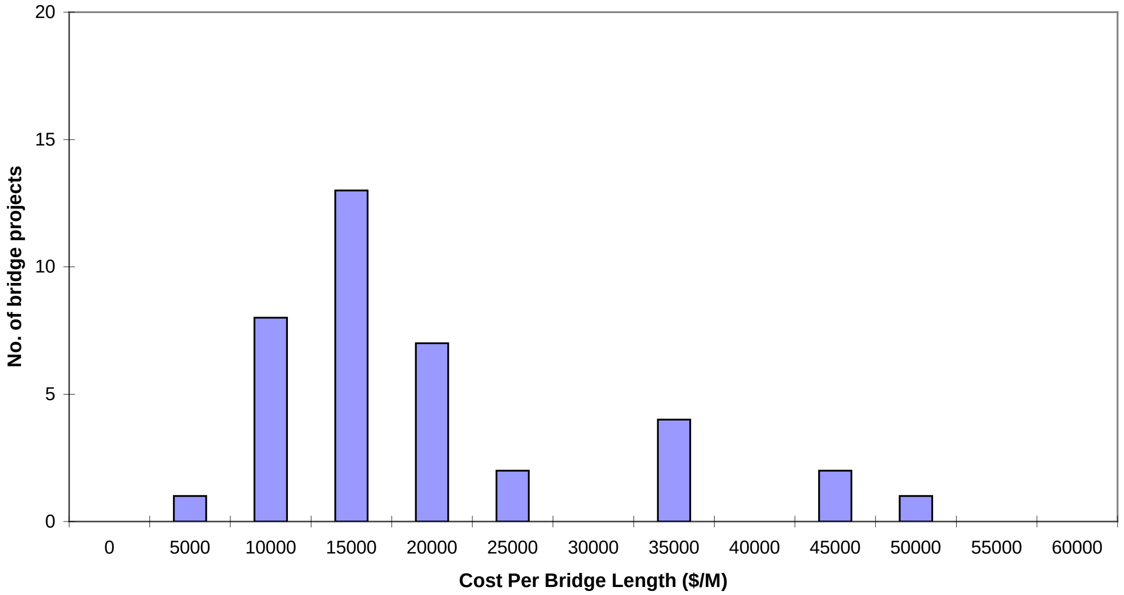


Figure 5.33. Statistical distribution of structures cost of widening per bridge length on FDOT BRRP District 2 projects (excluding $3million outlier project)

5.4 MMS Cost Data and Pontis Bridge Element Actions

As mentioned earlier a merge was made of the FDOT Work Library and the MMS Cost Data. The FDOT Bridge Work Library has the following fields: Site No., Datex (date information entered), Bridge No.; Activity; Unit of Measure; Priority; Instructions (Description of work to be done); Labrsor (Contract Labor Information); Labrcost (Direct or In-House labor Cost); Eqpcost (Direct or In-House Equipment Cost); Matcost (Direct or In-House Material Cost); clabcost (Contract labor Cost); ceqpcost (Contract Equipment Cost); cmatcost (Contract Material Cost); comp (Indicator if work is completed Y/N); compdate (Completion date for Direct or In-House work); ccompdte (Completion date for Contract work); and estunits (Estimated work in no. of units). The MMS Site Cost data has the following fields: Activity, Bridge No., Site No., Units Done, Labor cost, Equipment cost, Material cost, Total cost; and Fiscal Year.

The work library shows a description of MR&R work, the date it was identified as necessary and added to the system, an indication of whether the work was completed, and the date it was completed, means of getting the work done (in-house or by contract), the labor, equipment, and material costs (in-house), and/or contract costs. The MMS Site Cost data only shows cost information but identified by the Site No. The information in the Bridge Work Library is desired for the study of repair costs and their effectiveness because it has the pertinent details, but it was considered that the MMS Site Cost data may be useful as well. The Site No. is unique for each record in both data sources. A combination of the “Bridge No.” and “Site No.” fields therefore produced a new field that identifies a unique record of work on a specific bridge. This new field is now used to combine the Bridge Work Library and the MMS Site Cost data.

Interestingly, after the merge, it was observed that data from the two data sources are almost mutually exclusive, i.e., the MMS Site Cost Table had most of cost records corresponding to Bridge Work Library data with no cost information, and vice versa. The MMS Site Cost Table had 11,195 records, initially, before any refinement, with dates ranging from August 21,1996 to February 19, 2009. In a few cases where the two data sources cost information for the same record of work, differing quantity of estimated work done were indicated, in terms of quantity of units. But based on the reasoning that the Bridge Work Library typically records more complete details of work description and dates, the study used only the data from this source. Moreover, the MMS Site Cost data were recorded for fiscal years, not specific years. In other words, the MMS Site Cost data was abandoned.

Starting with an initial data set of the MMS Bridge Work Library with 78,509 records, some data cleaning and filtering were done to refine the data before the analyses. These initial records have a date range of March 15, 1993 to February 23, 2009 (the DATEX field). First, records with bad or missing *Bridge No.* and/or *Site No.* were deleted (40 records), as well as records not indicated in the *comp* field as being completed (726 records), or no date (*compdate* or *ccompdte* fields) indicated (613 records). The new date range is April 5, 1993 to February 4, 2009. Next, records with no costs indicated were deleted (49,766 records). The new refined data has 20,814 records, with a date range of April 6, 1993 to June 5, 2006, with these dates being the completion dates recorded for the work. It would be observed later that some of these records have costs recorded but they are zeroes and were removed from the data set, resulting in 17,907 final records.

Using a methodology similar to that employed during the FDOT agency cost study, the final MMS cost data were manually reviewed, going through each record’s “Instruction” field or the description of work done. Using the Action Subcategory (ActSubCat) definitions explained in the agency cost study, and shown in Table 5.17, each MMS work record is assigned a code to identify the type of work done. This assigned work code is better suited to Pontis bridge element work definitions. In assigning the ActSubCat code, caps are identified as beams, fences assigned to poles/signs, while “removing graffiti” and “removing vegetation” were classified as maintenance activities (400-Maint). The riprap repairs and erosion control work were classified as slope protection work. Also it should be noted that based on the work description in the MMS database, most of the work were either repairs or maintenance, with a few qualifying as replacement and rehabilitation. During the assignment of work objects, it was found necessary to add two new objects: 61 for emergency work; and 71 for guardrails, barriers, and parapets. Therefore codes such as 361 and 371 will respectively imply emergency type of repairs and repair of guardrails, barriers, and parapets.

Table 5.17. Action subcategory matrix (Source: Sobanjo and Thompson 2001)

			Action Category			
		Object	100-Replace	200-Rehab	300-Repair	400-Maint
Materials	0	Other material				4,714
	1	Deck	8,675	7,727	3,863	8,675
	2	Steel/coat (incl metal)	1,275	5,539	3,900	3,062
	3	Concrete		10,824	8,759	10,838
	4	Timber		1,258		1,225
	5	Masonry		3,034		7,210
	6	MSE		146		146
Hi-Maint	10	Other element				
	11	Joint	3,773	5,654	3,094	7,929
	12	Joint seal	7,544			
	13	Bearing (incl p/h)	6,879	6,878		3,878
	14	Railing	9,122			
Drainage	21	Slope prot	7,132	3,786		
	22	Channel		8,259		8,259
	23	Drain sys	3,969	24		3,969
Machinery	31	Machinery	201	201	154	201
	32	Cath prot	4,474			
Major	41	Beam	8,598			
	42	Truss/arch/box	234			
	43	Cable	41	41		
	44	Substr elem (exc cap)	11,286			
	45	Culvert	2,076			
	46	Appr slab	7,260	7,260		7,260
Appurtenances	51	Pole/sign	180			

New Actsubcats: 361- Emergency repair; 371 – Repair of barriers, guardrails, and parapets.

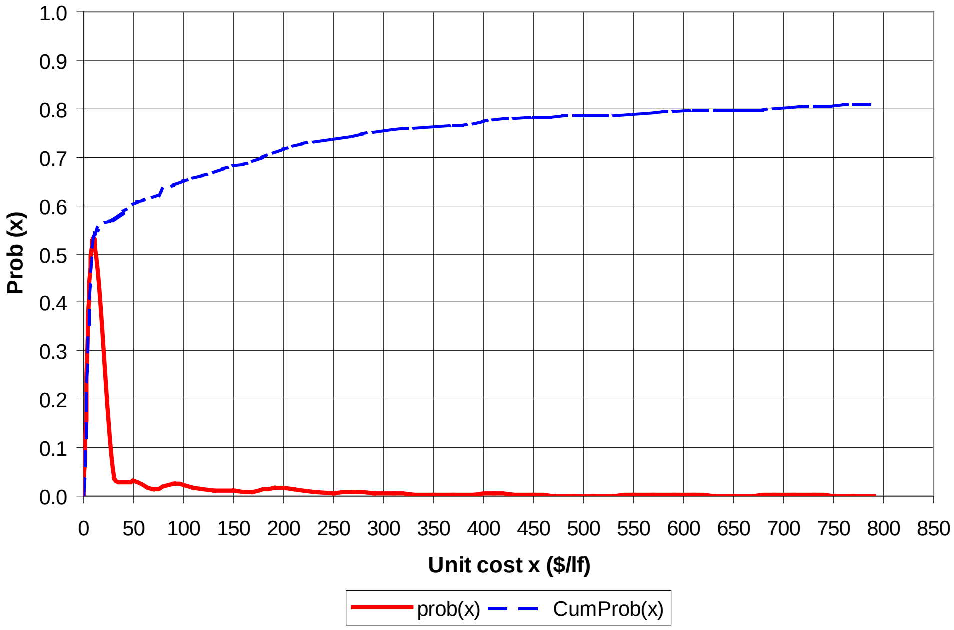


Figure 5.34. Statistical distribution of unit cost for Actsubcat 311LF, repair deck joints in $/LF, (75th percentile is approx. $300/LF)

The average unit costs, adjusted to 2009 dollars, and other pertinent basic descriptive statistics for the various action subcategories are shown in Table 5.18. Looking at the mean and median values, the results indicated presence of extreme values in the data and skewed distributions. Compared to typically known values, the mean values shown in Table 5.18 do not appear usable directly unless a further refinement is done statistically to ascertain reasons for the extreme values and the values adjusted accordingly. One of such methods would be to estimate a “trimmed” mean, where the suspected outliers at both tails of the distribution are excluded in computing a new mean. For example, consider element action with Actsubcat 311LF, repair of deck joints. The average using the entire data (806 actions) is $645.53/LF, with median $13.29/LF as shown in Table 5.18. The large difference between the mean and median values suggest a skew, and that there are many extremely small and extremely large values, with the large values strongly influencing the estimated mean. The skew is also indicated in Figure 5.34, showing the data only up to about the 80th percentile. Using a “trimmed” mean, excluding 25% at each of both extremes of the data, the estimated “trimmed” mean is $55.92/LF. This produces more reasonable results and the “trimmed” means (25% both tails) are shown for pertinent element actions in Table 5.18.

Table 5.18. Summary of bridge maintenance costs by action subcategories and unit

ACT SubCATUnit	UNIT COSTS ($/UNIT)					COUNT	Trimmed Mean
	MEAN	STD. DEV	MIN	MAX	MEDIAN		
111LF	330.49	1,763.47	0.01	16,214.58	1.66	96	
111LM	871.12	2,427.15	0.14	11,348.12	20.91	31	
112LF	433.51	1,935.11	0.01	22,056.42	0.64	508	
112LM	362.29	1,126.36	0.02	7,150.99	9.15	62	
113MH	231.71	481.29	5.33	1,092.21	11.60	5	
114LF	1,526.45	3,725.82	0.15	11,593.66	3.10	13	12.44
114MH	1,613.41	2,801.69	0.97	6,567.89	451.93	5	
151MH	291.58	371.71	0.37	1,509.03	152.63	34	154.35
301MH	11,036.66	76,211.03	0.01	899,062.50	72.45	322	115.42
301SF	1,174.01	7,527.15	0.01	117,577.78	92.31	383	151.36
301SM	2,241.83	7,463.98	0.01	71,813.86	518.56	208	583.01
303LF	604.53	1,089.19	0.44	5,326.51	117.58	48	
303SF	675.00	1,697.49	0.67	8,692.61	18.70	38	110.44
303MH	11,475.27	74,655.80	0.04	665,306.25	85.11	85	
306MH	207.34	274.42	0.39	666.13	50.95	9	
311LF	645.53	2,018.28	0.01	27,643.13	13.29	806	55.91
311LM	1,132.51	3,796.87	0.01	37,199.20	56.78	274	126.38
311MH	2,438.45	8,394.79	0.01	57,898.72	64.98	111	
311SF	918.24	4,428.09	0.01	34,042.97	53.92	89	
311SM	4,187.62	10,043.15	0.01	48,841.16	701.10	26	
313MH	8,544.44	70,917.46	0.02	646,693.05	70.17	83	182.76
314LF	289.29	1,033.60	0.01	11,014.20	17.80	256	38.40
314LM	945.27	1,728.09	0.01	10,684.88	264.62	50	399.36
314MH	12,209.18	78,704.08	0.01	701,075.18	17.22	88	
321LF	16.01	110.61	0.01	1,398.63	0.25	170	
321MH	799.09	3,440.80	0.01	104,044.17	40.37	1884	
321SF	94.41	400.62	0.01	2,589.57	1.62	88	3.45
322MH	415.58	1,058.72	0.08	2,816.18	19.38	7	
323SF	435.69	630.12	0.45	2,230.67	18.95	25	187.02
323MH	286.02	593.80	0.07	2,734.43	36.60	59	
331MH	271.72	751.25	0.01	14,515.64	39.30	1947	55.19
332MH	1,030.16	2,043.99	0.03	7,845.49	18.89	38	102.61
341CF	1,630.19	6,524.81	2.27	42,439.92	162.33	48	
341MH	2,131.22	17,845.75	0.01	514,024.00	107.08	1228	194.53
344CF	1,474.51	2,588.29	0.02	9,237.71	105.53	33	
344MH	2,930.76	29,828.46	0.01	702,554.65	75.79	939	135.26
345MH	833.85	6,339.23	0.00	97,660.96	59.56	238	158.10
346LF	102.37	275.83	0.02	2,043.11	0.60	108	
346MH	1,012.07	8,877.15	0.01	138,166.00	61.81	260	
346SF	506.32	986.11	0.07	13,104.26	269.49	253	315.71
346SM	1,159.00	2,207.45	0.01	16,599.90	522.34	108	552.28
351LF	263.06	589.95	0.17	3,266.78	66.89	31	96.19
351MH	310.42	964.48	0.04	7,184.00	55.84	133	68.99
361MH	2,251.56	3,276.72	0.01	8,376.23	1.16	7	
371LF	601.28	4,342.71	0.01	56,958.84	89.43	176	106.38
371LM	2,026.01	7,071.93	0.31	45,464.83	518.00	41	
371MH	917.34	4,384.70	0.02	36,718.19	53.27	128	

Table 5.18. Summary of bridge maintenance cost by action subcategories and unit (continued).

ACT SubCATUnit	UNIT COSTS ($/UNIT)					COUNT	Trimmed Mean
	MEAN	STD. DEV	MIN	MAX	MEDIAN		
400MH	368.79	960.39	0.01	7,533.68	43.89	196	69.71
400SF	155.79	256.04	0.01	688.66	9.01	11	32.37
401MH	151.17	717.73	0.01	5,941.42	2.35	75	7.37
401SF	268.05	872.30	0.01	4,525.24	5.67	27	23.70
402MH	67.29	119.40	0.01	325.67	9.70	7	
406MH	171.31	449.31	0.13	2,661.03	78.38	34	85.51
411LF	320.60	836.62	0.01	3,962.90	0.25	57	6.60
411LM	364.72	383.44	0.05	1,283.38	346.03	12	
411MH	134.81	295.73	0.01	1,303.50	2.81	39	9.76
411SF	120.70	250.28	0.01	1,034.83	0.43	24	6.99
413MH	367.74	610.40	0.01	2,114.23	16.47	31	114.93
421MH	201.87	513.65	0.01	5,425.46	10.54	443	32.02
421SF	42.82	116.95	0.01	453.65	0.48	15	3.61
422MH	372.29	810.88	0.01	5,433.26	68.64	63	90.82
422SF	1,558.51	2,394.43	0.11	6,066.17	402.03	6	
423MH	186.37	607.91	0.01	7,322.00	9.38	233	20.41
423SF	309.39	1,316.05	0.01	10,954.29	3.99	203	14.76
431MH	288.04	644.22	0.25	3,024.97	59.52	27	74.98
441EA	311.02	633.18	3.04	3,064.33	95.46	28	111.50
441MH	181.37	482.81	0.01	5,385.35	30.07	550	40.46
441SF	282.15	678.48	0.16	2,268.24	3.03	11	41.66
444MH	306.36	1,222.20	0.01	12,823.72	20.55	224	33.97
444SF	182.51	337.71	0.02	970.81	31.31	8	39.50
445MH	395.86	1,261.87	0.01	12,668.66	26.86	168	53.72
445SF	0.61	0.98	0.01	3.25	0.09	13	0.22
446MH	158.75	261.59	0.01	987.13	36.94	20	47.99
446SF	99.32	181.99	0.07	494.67	4.51	7	40.10
451MH	227.17	252.92	0.01	1,126.77	124.83	76	155.90

Also estimated was the timing of these actions or the age at which the actions were applied to the bridge. Shown in Table 5.19, these age parameters may be useful in estimating life cycle cost timings for the respective bridge maintenance actions. While the range of the timings are very large for most of the action subcategories, it shows that some actions are applied on the average, earlier in the service life of the bridge, and some applied later. Joint replacement and repairs (Action Subcategory Nos. 111 and 311) are applied to the bridge at an average age of about 25 years, while Joint seal (Action Subcategory No. 112) is done at about 30 years. Deck repairs (Action Subcategory No. 301) and concrete repairs (Action Subcategory No. 303) are done at the average age of about 32 years. Channel repairs (Action Subcategory No. 322) and cathodic protection repairs (Action Subcategory No. 332) are done on the average at the bridge age of 42 years. Cleaning joints (Action Subcategory No. 411) and cleaning slope protection (No. 421) were estimated as being done at the age of about 17 years and 29 years respectively. Cleaning MSE walls (Action Subcategory No. 406) indicated an average of application at about 9 years, but this may be just reflecting the recent use of this technology on bridges.

Table 5.19. Summary of age of bridge at maintenance and repair actions

Action SubCategory	AGE OF BRIDGE AT ACTION (YRS.)					COUNT
	MEAN	STD. DEV	MIN	MAX	MEDIAN	
111	25.2	11.5	3.0	95.0	24.0	135
112	29.9	11.1	1.0	72.0	30.0	579
113	23.0	10.0	15.0	34.0	16.0	5
114	29.5	15.5	1.0	60.0	33.5	22
151	28.6	11.1	7.0	60.0	31.0	38
301	32.1	13.8	2.0	95.0	33.0	953
303	31.9	15.3	3.0	78.0	32.0	208
306	13.2	15.3	2.0	40.0	6.0	9
311	25.9	13.1	1.0	74.0	26.0	1349
313	29.3	13.2	4.0	60.0	29.0	85
314	34.9	12.9	1.0	76.0	34.0	407
321	27.0	14.9	0.0	97.0	28.0	2229
322	41.9	15.1	19.0	72.0	37.0	15
323	19.0	15.1	0.0	77.0	14.5	102
331	33.4	15.5	0.0	88.0	35.0	1989
332	41.9	12.6	10.0	71.0	44.0	39
341	31.2	13.6	0.0	76.0	32.0	1295
344	31.2	15.1	0.0	86.0	32.0	1006
345	36.5	13.8	2.0	77.0	34.0	241
346	24.9	14.0	0.0	86.0	25.0	777
351	27.8	14.0	0.0	71.0	30.0	184
361	42.3	11.2	33.0	59.0	36.5	8
371	24.7	13.4	1.0	95.0	26.0	359
400	29.9	14.4	2.0	73.0	29.0	254
401	23.3	12.8	0.0	68.0	24.5	130
402	42.1	5.4	37.0	52.0	40.0	7
406	8.6	6.3	4.0	36.0	6.0	39
411	17.1	14.4	0.0	69.0	13.0	146
413	32.5	9.4	11.0	57.0	33.0	33
421	28.8	11.1	2.0	98.0	30.0	501
422	33.7	15.0	1.0	72.0	35.0	89
423	27.9	15.6	1.0	75.0	30.0	532
431	28.7	14.7	2.0	61.0	31.5	30
441	28.6	12.2	1.0	71.0	29.0	597
444	26.7	14.5	1.0	74.0	27.0	249
445	34.9	15.5	1.0	70.0	34.0	211
446	24.3	11.9	5.0	46.0	24.0	32
451	32.2	7.6	9.0	42.0	34.0	79

5.5 Conclusions

Many useful cost data were obtained in this study, but the more useful estimates appear to be for project level actions rather than the element actions. In other words, good estimates were derived for projects such as cathodic protection and painting projects on a bridge, rather the specific element actions for cathodic protection of the bridge substructure element or structural painting of the bridge superstructure element. These project costs may typically include other cost items such as mobilization, maintenance of traffic, and even some other element actions. Meaningful statistical relationships were also established between costs and bridge attributes, including age of bridge at which work was done, as well as relationship between Maintenance of Traffic (MOT) costs and traffic characteristics of the under roadways. In the review of bridge costs at FDOT District Two, it was observed that on bridge rehabilitation and replacement projects, structures cost was the predominant portion of the total costs, constituting between 67% and 91% of the total project costs; Maintenance of Traffic (MOT) costs was between 1% and 14%; while Mobilization costs range from 3% to 13%.

Below in Tables 5.20 and 5.21 are shown the values estimated from the statewide bid data, for the unit costs (per deck area in sq. meter) of Mobilization and Maintenance of Traffic (MOT), respectively, for bridges identified with such bid unit cost items. The sum of these two unit costs were compared to the mean overall unit cost of the type of work, for example, the ratio of the unit costs (combined) of Mobilization and MOT, relative to the mean unit cost of cathodic protection work is about 8%. For major rehabilitation, this ratio is about 16% while for fender work, the ratio is about 17%. Looking at the study of BRRP projects in FDOT District Two, it was observed (from Tables 5.9 to 5.15) that the combined Mobilization and MOT unit costs varied from low values of about 4% for cathodic protection to about 27% for scour counter measures work.

Table 5.20. Mobilization unit costs

	COSTS PER DECK AREA ($/SQ. M)					No. of
Type of Work	MEAN	STD. DEV	MIN	MAX	MEDIAN	Projects
Cathodic Protection	6.60	6.65	2.73	16.54	3.56	4
Fender	27.94	25.25	1.68	69.11	23.56	7
Major Rehabilitation*	82.35	142.40	0.91	642.81	25.47	23
Painting	7.33	5.90	1.42	16.09	8.29	5
Riprap	103.10	88.26	30.37	287.43	79.10	7
All projects (with Mobilization bid costs)	61.16	110.08	0.34	642.81	21.21	47

* majority are superstructure related.

Table 5.21. Maintenance of Costs (MOT) Unit Costs

	COSTS PER DECK AREA ($/SQ. M)					No. of
Type of Work	MEAN	STD. DEV	MIN	MAX	MEDIAN	Projects
Cathodic Protection	2.75	1.41	0.73	3.72	3.27	4
Fender	9.69	12.37	0.84	31.76	3.88	7
Major Rehabilitation*	10.33	13.42	0.17	47.05	3.52	22
Painting	2.38	1.76	0.82	5.18	1.46	5
Riprap	17.34	18.28	5.99	56.70	8.93	7
All projects (with MOT bid costs)	9.57	13.06	0.17	56.70	3.72	46

* majority are superstructure related.

In the FDOT District Two data, structures unit costs of scour counter measures work was about 67% of the overall construction costs, while those of fender repairs and replacement, painting and repairs, including steel repairs, range between 77% and 86% of the construction unit cost, and that of cathodic protection was about 90%. The Apparently, cathodic protection work is mostly structures work in terms of unit costs. It should be noted that these are construction estimate costs and there are still other costs, apart from the Mobilization and MOT costs, i.e., cost of engineering work and construction costs of work items such as roadway, lighting, etc. Based on these two sources of information (statewide data and FDOT District Two), it can be assumed that, if the engineering costs are uniformly spread over the various work components (roadway, lighting, structures, etc.), the bridge rehabilitation and repair unit costs will comprise 80% structures-related cost and 20% other costs. There are some special cases for cathodic protection (90% structures-related cost) and scour countermeasures (70% structures-related cost).

The primary goal of this research task was to estimate unit costs for use in the Pontis Bridge Management System, specifically, for use at the bridge element action level. The bridge element action costs obtained are summarized in Tables 5.22 and 5.23, indicating the two sources, i.e., the MMS cost database, or the statewide bid cost database. As expected, the bid data contributed to majority of the replacement and rehabilitation actions while the MMS cost database provided cost for much of the repair and maintenance actions. The former are basically contractors' bids to perform construction services on the bridge, and can be considered very reliable. On the other hand, MMS costs are suspect and may need to be "cleaned up" before use in the Pontis BMS. An example of such "cleaning up" may involve estimating the "trimmed" mean. This was demonstrated earlier in this report, for the action with Actsubcat no. 311LF, resulting in a "trimmed" MMS unit cost estimate of about $56/LF, which is closer to the bid unit cost of $78.62/LF (Table 5.23).

In establishing the Pontis unit costs for 2009, new costs from the current study were utilized to update the existing cost database. Unfortunately only 18 element actions' unit costs were directly usable in Pontis, primarily because the data collection process for bridge work is still dependent on the traditional FDOT databases which are not really compatible with Pontis element action unit formats. This resulted in 195 out of the overall 811 element-state-actions (e.g., element 12, state 2, action key 1), or 24% being directly useful. The next step taken was to update the existing unit costs collected in 2001, by the FDOT PDC factor (time-related factors) to 2009 values; in this case the factor is 1.7122 to relate 2001 to 2009 values. The existing unit costs from 2001 were collected in a relatively more intensive process, including use of expert opinions of the bridge managers, and thus can be considered very reliable values.

The other issue has to do with "spreading" the actsubcat unit costs over the various element actions, i.e., for specific elements. For example, as shown in Table 5.24, the single unit cost of $264.15/M estimated for action subcategory or asubcat no. 111 "Replace joint" is assigned over the following elements: no. 300 "Strip Seal Expansion Joint," no. 301 "Pourable Joint Seal," no. 302 "Compression Joint Seal," no. 303 "Assembly Joint/Seal (modular)," no. 304 "Open Expansion Joint," and no. 399 "Other Expansion Joint." To do this, a conservative approach was used, matching the new unit cost to the lowest unit cost among these joint elements, and then using the ratio of the existing unit costs to the lowest cost to estimate the new element-specific unit costs. For example, the new unit cost for asubcat no. 111 "Replace joint" of $264.15/M is matched to the lowest existing 2001 unit cost among the pertinent five elements, i.e. $524.50/M for element nos. 300 and 301. Using the ratio of new to existing lowest in the group, the new unit cost of element no. 304 (originally $1306.96/M in 2001) will now be computed as ($1306.96)*($264.15 /$524.50) or $658.22/M.

The final costs are shown in Table 5.25. It should be noted that the costs estimated during the current study are construction costs. It is necessary to adjust for the total costs and break them into variable and fixed unit cost components, i.e. Pontis database fields varunitco and fixunitco respectively, both in 2009 dollars. Engineering costs are assumed to be 10% of the total project costs, and as discussed earlier on the analyses of MOT and mobilizations costs, the variable unit costs are taken to be 80% of the overall unit cost for all elements except for substructures, where the ratio is 90%.

Looking at Table 5.25, the relative changes (ratio) of the updated (2009) unit costs from the existing (2001) unit costs are shown in the "Change" column for those element action costs where new costs were available. It could be seen that only one of the costs, i.e. costs for asubcat no. 311 or "Repair joint' has new unit costs about the same as those of the existing unit costs while costs for asubcat no. 141 "Replace beam" are about 30% more for the newly estimated costs. The unit costs for asubcat no. 411 or "Maintain joint' is about 80% of the old costs and asubcat 303 "Repair Concrete" is now estimated to cost about 60% of the existing unit cost. New unit costs for asubcat no. 102 "Replace Steel/coat (incl metal)," and asubcat no. 400 "Maintain Other Material" were observed to be roughly twice the existing unit costs. Some element actions such as "Clean and replace joint," i.e., asubcat no. 112, and "Replace railing," asubcat no. 114, have their new unit costs about 2.5 times the existing unit costs. Unit costs for asubcat no. 111 "Replace joints" were about one-thirds the existing costs while asubcat nos. 211 "Rehab joint" has newly estimated unit costs being about half the values of the existing values.

A review and some analyses were also done on the FDOT's current use of MMS in capturing bridge action costs, which relies primarily on the MMS activity number to identify the work done to the bridge. The discussions and results are summarized in Appendix A, including mean unit costs, bridge age at actions, etc., as well an investigation on the relationship between the activity numbers in MMS and the Pontis-compatible Action subcategories. This is important because the MMS cost database is currently the FDOT's primary source for its annual reports on bridge maintenance and repair expenditures, and the costs are typically summarized by the MMS Activity Nos. It was observed that MMS Activity No. 805 (Bridge Joint Repair) was used primarily (80% of recorded actions) for bridge deck joints (Action Subcategory Nos. 111, 112, 311, and 411). Predominant element actions in MMS Activity No. 806 (Bridge Deck Maintenance and Repair) are Action Subcategory Nos. 301, 346, and 423 which are related to bridge deck maintenance, approach roadways, and cleaning drainage systems, respectively. MMS Activity No. 810 (Bridge Handrail Maintenance) comprises mostly of repair actions for handrails (Action Subcategory No. 314) and repairs of guardrails, barriers, and parapets (Action Subcategory No. 371). While MMS Activity No. 825 (Superstructure Maintenance and Repair) covered many element actions, over half of the actions observed were related to repair of beams (No. 341). Repair of slope pavement and substructure (Action Subcategory Nos. 321 and 344 respectively) dominate actions under MMS Activity No 845 (Substructure Maintenance and Repair), as well some significant number of actions related to maintenance of slope pavement (Action Subcategory No. 421) and maintenance of beams (Action Subcategory No. 441), with the latter being mostly due to the fact that caps are classified as beams under the Action Subcategory scheme.

Table 5.22. Combined list of bridge element action unit costs for replacement and rehabilitation

		MMS COST DATABASE							Trimmed*	STATEWIDE BID COST DATABASE						
ActSubCat	Description	Unit	Mean	Std Dev	Min	Max	Median	Count	Mean	Unit	Mean	Std Dev	Min	Max	Median	Count
100	Replace Other material															
101	Replace Deck															
102	Replace Steel/coat (incl metal)									LF	99.89	6.71	95.14	104.63	99.89	2
103	Replace Concrete															
104	Replace Timber															
105	Replace Masonry															
106	Replace MSE															
110	Replace Other element															
111	Replace Joint	LF	330.49	1,763.47	0.01	16,214.58	1.66	96		LF	80.53	85.55	29.57	283.85	47.23	15
112	Replace Joint seal	LF	433.51	1,935.11	0.01	22,056.42	0.64	508		LF	130.01	175.46	46.21	870.60	65.30	46
113	Replace Bearing (incl p/h)	MH	231.71	481.29	5.33	1,092.21	11.60	5		EA	5,769.86	2,660.48	3,047.10	14,510.00	4,933.40	17
114	Replace Railing	LF	1,526.45	3,725.82	0.15	11,593.66	3.10	13		LF	159.53	296.80	29.02	5,017.60	116.08	296
121	Replace Slope prot									SY	107.47	70.10	45.16	470.40	82.71	53
122	Replace Channel															
123	Replace Drain sys									LF	108.75	30.49	87.06	165.77	87.06	7
131	Replace Machinery															
132	Replace Cath prot									EA	1,193.89	581.66	569.21	2,547.96	1,197.08	11
141	Replace Beam									LF	293.88	214.19	100.93	1,596.10	245.17	126
142	Replace Truss/arch/box															
143	Replace Cable															
144	Replace Substr elem (exc cap)															
145	Replace Culvert															
146	Replace Appr slab															
151	Replace Poles/sign	MH	291.58	371.71	0.37	1,509.03	152.63	34		AS	68,922.50	5,130.06	65,295.00	72,550.00	68,922.50	2
200	Rehab Other material															
201	Rehab Deck															
202	Rehab Steel/coat (incl metal)															
203	Rehab Concrete															
204	Rehab Timber															
205	Rehab Masonry															
206	Rehab MSE															
210	Rehab Other element															
211	Rehab Joint									LF	85.75	118.59	28.37	889.37	49.96	99
212	Rehab Joint seal															
213	Rehab Bearing (incl p/h)															
214	Rehab Railing															
221	Rehab Slope prot									LF	99.61	89.63	29.02	365.65	79.81	12
222	Rehab Channel															
223	Rehab Drain sys															
231	Rehab Machinery															
232	Rehab Cath prot															
241	Rehab Beam															
242	Rehab Truss/arch/box															
243	Rehab Cable															
244	Rehab Substr elem (exc cap)									LF	686.04	487.31	130.59	1,664.77	584.17	12
245	Rehab Culvert															
246	Rehab Appr slab															
251	Rehab Poles/sign									AS	10,812.00	12,253.65	174.12	29,020.00	7,255.00	5

* Estimated excluding 25% data outliers from top and bottom tails of the data.

Table 5.23. Combined list of bridge element action unit costs for repair and maintenance

		MMS COST DATABASE							Trimmed*	STATEWIDE BID COST DATABASE						
ActSubCat	Description	Unit	Mean	Std Dev	Min	Max	Median	Count	Mean	Unit	Mean	Std Dev	Min	Max	Median	Count
300	Repair Other material															
301	Repair Deck	SF	1,174.01	7,527.15	0.01	117,577.78	92.31	383	151.36							
302	Repair Steel/coat (incl metal)															
303	Repair Concrete	SF	675.00	1,697.49	0.67	8,692.61	18.70	38	110.44	CF	1,053.92	1,274.55	1.14	7,865.69	689.92	57
304	Repair Timber															
305	Repair Masonry															
306	Repair MSE	MH	207.34	274.42	0.39	666.13	50.95	9								
310	Repair Other element															
311	Repair Joint	LF	645.53	2,018.28	0.01	27,643.13	13.29	806	55.91	LF	78.62	69.71	14.53	167.18	37.55	11
312	Repair Joint seal															
313	Repair Bearing (incl p/h)	MH	8,544.44	70,917.46	0.02	646,693.05	70.17	83	182.76							
314	Repair Railing	LF	289.29	1,033.60	0.01	11,014.20	17.80	256	38.40							
321	Repair Slope prot	SF	94.41	400.62	0.01	2,589.57	1.62	88	3.45							
322	Repair Channel	MH	415.58	1,058.72	0.08	2,816.18	19.38	7								
323	Repair Drain sys	SF	435.69	630.12	0.45	2,230.67	18.95	25	187.02							
331	Repair Machinery	MH	271.72	751.25	0.01	14,515.64	39.30	1,947	55.19							
332	Repair Cath prot	MH	1,030.16	2,043.99	0.03	7,845.49	18.89	38	102.61							
341	Repair Beam	MH	2,131.22	17,845.75	0.01	514,024.00	107.08	1,228	194.53	LF	3,986.53	3,973.19	1,177.07	6,796.00	3,986.53	2
342	Repair Truss/arch/box															
343	Repair Cable															
344	Repair Substr elem (exc cap)	MH	2,930.76	29,828.46	0.01	702,554.65	75.79	939	135.26							
345	Repair Culvert	MH	833.85	6,339.23	0.00	97,660.96	59.56	238	158.10							
346	Repair Appr slab	SF	506.32	986.11	0.07	13,104.26	269.49	253	315.71							
351	Repair Poles/sign	LF	263.06	589.95	0.17	3,266.78	66.89	31	96.19							
400	Maint Other material	SF	155.79	256.04	0.01	688.66	9.01	11	32.37	SF	1.82	1.50	0.38	9.58	1.24	90
401	Maint Deck	SF	268.05	872.30	0.01	4,525.24	5.67	27	23.70	SF	0.66	0.47	0.29	1.45	0.48	21
402	Maint Steel/coat (incl metal)	MH	67.29	119.40	0.01	325.67	9.70	7								
403	Maint Concrete									SF	1.82	1.50	0.38	9.58	1.24	90
404	Maint Timber															
405	Maint Masonry															
406	Maint MSE	MH	171.31	449.31	0.13	2,661.03	78.38	34	85.51							
410	Maint Other element															
411	Maint Joint	LF	320.60	836.62	0.01	3,962.90	0.25	57	6.60							
412	Maint Joint seal															
413	Maint Bearing (incl p/h)	MH	367.74	610.40	0.01	2,114.23	16.47	31	114.93							
414	Maint Railing															
421	Maint Slope prot	SF	42.82	116.95	0.01	453.65	0.48	15	3.61							
422	Maint Channel	SF	1,558.51	2,394.43	0.11	6,066.17	402.03	6								
423	Maint Drain sys	SF	309.39	1,316.05	0.01	10,954.29	3.99	203	14.76							
431	Maint Machinery	MH	288.04	644.22	0.25	3,024.97	59.52	27	74.98							
432	Maint Cath prot															
441	Maint Beam	EA	311.02	633.18	3.04	3,064.33	95.46	28	111.50							
442	Maint Truss/arch/box															
443	Maint Cable															
444	Maint Substr elem (exc cap)	SF	182.51	337.71	0.02	970.81	31.31	8	39.50							
445	Maint Culvert	SF	0.61	0.98	0.01	3.25	0.09	13	0.22							
446	Maint Appr slab	SF	99.32	181.99	0.07	494.67	4.51	7	40.10							
451	Maint Poles/sign	MH	227.17	252.92	0.01	1,126.77	124.83	76	155.90							
361	Repair (Emergency)**	MH	2,251.56	3,276.72	0.01	8,376.23	1.16	7								
371	Repair (Barriers, Guardrails)**	LF	601.28	4,342.71	0.01	56,958.84	89.43	176								

* Estimated excluding 25% data outliers from top and bottom tails of the data.

* New suggetsed Actsubcategories; not in the original list.

Table 5.24. Sample list of updated unit costs for Pontis element actions

elemkey	metricunit	skey	akey	wholeflag	asubcat	varunitco	fixunitco	Cost2001	ExistCost2009	Cost2009	AdjCost2009	AdjElemCost2009	ElemCost2009	varunitco2009	fixunitco2009	Change
12	sq.m.	5	2	1	101	322.95	100.23	423.18	724.57	NA	724.57		724.57	579.66	144.91	
13	sq.m.	5	2	1	101	333.72	103.57	437.29	748.73	NA	748.73		748.73	598.98	149.75	
28	sq.m.	5	2	1	101	376.78	116.93	493.71	845.33	NA	845.33		845.33	676.26	169.07	
29	sq.m.	5	2	1	101	430.6	133.63	564.23	966.07	NA	966.07		966.07	772.86	193.21	
30	sq.m.	5	2	1	101	17381.06	5394.12	22775.18	38995.66	NA	38995.66		38995.66	31196.53	7799.13	
31	sq.m.	3	2	1	101	107.65	33.41	141.06	241.52	NA	241.52		241.52	193.22	48.30	
31	sq.m.	4	1	1	101	107.65	33.41	141.06	241.52	NA	241.52		241.52	193.22	48.30	
32	sq.m.	3	2	1	101	86.12	26.73	112.85	193.22	NA	193.22		193.22	154.58	38.64	
32	sq.m.	4	1	1	101	129.18	40.09	169.27	289.82	NA	289.82		289.82	231.86	57.96	
38	sq.m.	5	2	1	101	322.95	100.23	423.18	724.57	NA	724.57		724.57	579.66	144.91	
39	sq.m.	5	2	1	101	333.72	103.57	437.29	748.73	NA	748.73		748.73	598.98	149.75	
54	sq.m.	3	2	1	101	10.77	3.34	14.11	24.16	NA	24.16		24.16	19.33	4.83	
54	sq.m.	4	1	1	101	10.77	3.34	14.11	24.16	NA	24.16		24.16	19.33	4.83	
55	sq.m.	3	2	1	101	32.3	10.02	42.32	72.46	NA	72.46		72.46	57.97	14.49	
55	sq.m.	4	1	1	101	32.3	10.02	42.32	72.46	NA	72.46		72.46	57.97	14.49	
98	sq.m.	5	2	1	101	322.95	100.23	423.18	724.57	NA	724.57		724.57	579.66	144.91	
99	sq.m.	5	2	1	101	333.72	103.57	437.29	748.73	NA	748.73		748.73	598.98	149.75	
102	m.	4	2	0	102	9186.8	3062.27	12249.07	20972.86	327.63	327.63	36693.60	40770.67	32616.53	8154.13	1.94
107	m.	4	2	0	102	170.61	56.87	227.48	389.49	327.63	327.63	681.44	757.16	605.73	151.43	1.94
113	m.	4	2	0	102	108.27	36.09	144.36	247.17	327.63	327.63	432.45	480.50	384.40	96.10	1.94
121	m.	4	2	0	102	387.16	129.05	516.21	883.85	327.63	327.63	1546.37	1718.19	1374.55	343.64	1.94
126	m.	4	2	0	102	492.15	164.05	656.2	1123.55	327.63	327.63	1965.73	2184.14	1747.31	436.83	1.94
131	m.	4	2	0	102	2296.7	765.57	3062.27	5243.22	327.63	327.63	9173.41	10192.68	8154.14	2038.54	1.94
141	m.	4	2	0	102	1378.02	459.34	1837.36	3145.93	327.63	327.63	5504.04	6115.60	4892.48	1223.12	1.94
152	m.	4	2	0	102	177.17	59.06	236.23	404.47	327.63	327.63	707.66	786.28	629.03	157.26	1.94
160	ea.	4	2	0	102	708	236	944	1616.32	327.63	327.63	2827.87	3142.08	2513.66	628.42	1.94
161	ea.	4	2	0	102	708	236	944	1616.32	327.63	327.63	2827.87	3142.08	2513.66	628.42	1.94
202	ea.	4	2	0	102	250	83.33	333.33	570.73	327.63	327.63	998.53	1109.48	998.53	110.95	1.94
231	m.	3	2	0	102	246.08	82.03	328.11	561.79	327.63	327.63	982.89	1092.10	982.89	109.21	1.94
231	m.	4	2	0	102	190.3	63.43	253.73	434.44	327.63	327.63	760.08	844.53	760.08	84.45	1.94
487	m.	1	2	0	102	82.03	27.34	109.37	187.26	327.63	327.63	327.63	364.03	291.23	72.81	1.94
487	m.	4	2	0	102	170.61	56.87	227.48	389.49	327.63	327.63	681.44	757.16	605.73	151.43	1.94
488	m.	4	2	0	102	170.61	56.87	227.48	389.49	327.63	327.63	681.44	757.16	605.73	151.43	1.94
496	ea.	4	2	0	102	5000	1666.67	6666.67	11414.67	327.63	327.63	19970.83	22189.81	17751.85	4437.96	1.94
497	ea.	4	2	0	102	5000	1666.67	6666.67	11414.67	327.63	327.63	19970.83	22189.81	17751.85	4437.96	1.94
550	ea.	4	2	0	102	5000	1666.67	6666.67	11414.67	327.63	327.63	19970.83	22189.81	17751.85	4437.96	1.94
562	ea.	4	2	0	102	5000	1666.67	6666.67	11414.67	327.63	327.63	19970.83	22189.81	17751.85	4437.96	1.94
563	ea.	4	2	0	102	2500	833.33	3333.33	5707.33	327.63	327.63	9985.40	11094.89	8875.91	2218.98	1.94
242	m.	4	2	0	104	8858.7	2531.06	11389.76	19501.55	NA	19501.55		19501.55	15601.24	3900.31	
300	m.	3	2	0	111	400.28	124.22	524.5	898.05	264.15	264.15	264.15	293.50	234.80	58.70	0.33
301	m.	3	2	0	111	400.28	124.22	524.5	898.05	264.15	264.15	264.15	293.50	234.80	58.70	0.33
302	m.	3	2	0	111	498.71	154.77	653.48	1118.89	264.15	264.15	329.11	365.68	292.54	73.14	0.33
303	m.	3	2	0	111	1378.02	427.66	1805.68	3091.69	264.15	264.15	909.39	1010.43	808.35	202.09	0.33
304	m.	3	2	0	111	997.42	309.54	1306.96	2237.78	264.15	264.15	658.22	731.36	585.09	146.27	0.33
399	m.	3	2	0	111	997.42	309.54	1306.96	2237.78	264.15	264.15	658.22	731.36	585.09	146.27	0.33

Table 5.25. Complete list of updated unit costs for Pontis element actions

elemkey	metricunit	skey	akey	wholeflag	asubcat	varunitco	fixunitco	Cost2001	ExistCost2009	Cost2009	AdjCost2009	AdjElemCost2009	ElemCost2009	varunitco2009	fixunitco2009	Change
12	sq.m.	1	1	1	132	958.3	297.4	1255.7	2150.01	NA	2150.01		2150.01	1720.01	430.00	
12	sq.m.	1	2	0	401	0	0	0	0.00	7.06	7.06	0.00	0.00	0.00	0.00	
12	sq.m.	2	1	1	401	53.83	16.71	70.54	120.78	7.06	7.06	17.65	19.61	15.69	3.92	0.16
12	sq.m.	2	2	1	132	792.63	245.99	1038.62	1778.33	NA	1778.33		1778.33	1422.66	355.67	
12	sq.m.	3	1	1	401	107.65	33.41	141.06	241.52	7.06	7.06	35.29	39.22	31.37	7.84	0.16
12	sq.m.	3	2	1	132	1390.52	431.54	1822.06	3119.73	NA	3119.73		3119.73	2495.78	623.95	
12	sq.m.	4	1	1	401	215.3	66.82	282.12	483.05	7.06	7.06	70.59	78.43	62.74	15.69	0.16
12	sq.m.	4	2	1	132	1627.99	505.24	2133.23	3652.52	NA	3652.52		3652.52	2922.01	730.50	
12	sq.m.	5	1	1	132	2607.18	809.12	3416.3	5849.39	NA	5849.39		5849.39	4679.51	1169.88	
12	sq.m.	5	2	1	101	322.95	100.23	423.18	724.57	NA	724.57		724.57	579.66	144.91	
13	sq.m.	1	1	0	401	21.53	6.68	28.21	48.30	7.06	7.06	7.06	7.84	6.27	1.57	0.16
13	sq.m.	2	1	1	301	53.83	16.71	70.54	120.78	1628.64	1628.64	1628.64	1809.60	1447.68	361.92	14.98
13	sq.m.	3	1	1	301	107.65	33.41	141.06	241.52	1628.64	1628.64	3256.81	3618.68	2894.94	723.74	14.98
13	sq.m.	3	2	1	201	406.92	126.29	533.21	912.96	NA	912.96		912.96	730.37	182.59	
13	sq.m.	4	1	1	301	215.3	66.82	282.12	483.05	1628.64	1628.64	6513.62	7237.36	5789.88	1447.47	14.98
13	sq.m.	4	2	1	201	406.92	126.29	533.21	912.96	NA	912.96		912.96	730.37	182.59	
13	sq.m.	5	1	1	201	406.92	126.29	533.21	912.96	NA	912.96		912.96	730.37	182.59	
13	sq.m.	5	2	1	101	333.72	103.57	437.29	748.73	NA	748.73		748.73	598.98	149.75	
28	sq.m.	1	1	0	401	43.06	13.36	56.42	96.60	7.06	7.06	14.12	15.69	12.55	3.14	0.16
28	sq.m.	2	1	1	400	5.38	1.67	7.05	12.07	19.56	19.56	19.56	21.73	17.39	4.35	1.80
28	sq.m.	3	1	1	402	10.77	3.59	14.36	24.59	NA	24.59		24.59	19.67	4.92	
28	sq.m.	3	2	1	202	96.89	32.3	129.19	221.20	NA	221.20		221.20	176.96	44.24	
28	sq.m.	4	1	1	302	107.65	35.88	143.53	245.75	NA	245.75		245.75	196.60	49.15	
28	sq.m.	4	2	1	202	161.48	53.83	215.31	368.65	NA	368.65		368.65	294.92	73.73	
28	sq.m.	5	1	1	202	215.3	71.77	287.07	491.52	NA	491.52		491.52	393.22	98.30	
28	sq.m.	5	2	1	101	376.78	116.93	493.71	845.33	NA	845.33		845.33	676.26	169.07	
29	sq.m.	1	1	0	401	43.06	13.36	56.42	96.60	7.06	7.06	14.12	15.69	12.55	3.14	0.16
29	sq.m.	2	1	1	400	5.38	1.67	7.05	12.07	19.56	19.56	19.56	21.73	17.39	4.35	1.80
29	sq.m.	3	1	1	402	10.77	3.59	14.36	24.59	NA	24.59		24.59	19.67	4.92	
29	sq.m.	3	2	1	202	116.26	38.75	155.01	265.41	NA	265.41		265.41	212.33	53.08	
29	sq.m.	4	1	1	302	129.18	43.06	172.24	294.91	NA	294.91		294.91	235.93	58.98	
29	sq.m.	4	2	1	202	193.77	64.59	258.36	442.36	NA	442.36		442.36	353.89	88.47	
29	sq.m.	5	1	1	202	258.36	86.12	344.48	589.82	NA	589.82		589.82	471.85	117.96	
29	sq.m.	5	2	1	101	430.6	133.63	564.23	966.07	NA	966.07		966.07	772.86	193.21	
30	sq.m.	1	1	0	401	0	0	0	0.00	7.06	7.06	0.00	0.00	0.00	0.00	
30	sq.m.	2	1	1	401	115.83	35.95	151.78	259.88	7.06	7.06	37.98	42.20	33.76	8.44	0.16
30	sq.m.	3	1	1	402	347.6	115.87	463.47	793.55	NA	793.55		793.55	634.84	158.71	
30	sq.m.	3	2	1	202	115.83	38.61	154.44	264.43	NA	264.43		264.43	211.55	52.89	
30	sq.m.	4	1	1	302	463.54	154.51	618.05	1058.23	NA	1058.23		1058.23	846.58	211.65	
30	sq.m.	4	2	1	202	2954.78	984.93	3939.71	6745.57	NA	6745.57		6745.57	5396.46	1349.11	
30	sq.m.	5	1	1	202	11587.34	3862.45	15449.79	26453.13	NA	26453.13		26453.13	21162.50	5290.63	
30	sq.m.	5	2	1	101	17381.06	5394.12	22775.18	38995.66	NA	38995.66		38995.66	31196.53	7799.13	

Table 5.25. Complete list of updated unit costs for Pontis element actions (continued)

elemkey	metricunit	skey	akey	wholeflag	asubcat	varunitco	fixunitco	Cost2001	ExistCost2009	Cost2009	AdjCost2009	AdjElemCost2009	ElemCost2009	varunitco2009	fixunitco2009	Change
31	sq.m.	1	1	0	401	21.53	6.68	28.21	48.30	7.06	7.06	7.06	7.84	6.27	1.57	0.16
31	sq.m.	2	1	1	204	64.59	20.05	84.64	144.92	NA	144.92		144.92	115.94	28.98	
31	sq.m.	3	1	1	204	0	0	0	0.00	NA	0.00		0.00	0.00	0.00	
31	sq.m.	3	2	1	101	107.65	33.41	141.06	241.52	NA	241.52		241.52	193.22	48.30	
31	sq.m.	4	1	1	101	107.65	33.41	141.06	241.52	NA	241.52		241.52	193.22	48.30	
31	sq.m.	4	2	1	301	1811.1	562.07	2373.17	4063.34	1628.64	1628.64	54792.03	60880.03	48704.03	12176.01	14.98
32	sq.m.	1	1	0	401	21.53	6.68	28.21	48.30	7.06	7.06	7.06	7.84	6.27	1.57	0.16
32	sq.m.	2	1	1	401	43.06	13.36	56.42	96.60	7.06	7.06	14.12	15.69	12.55	3.14	0.16
32	sq.m.	2	2	1	204	53.83	16.71	70.54	120.78	NA	120.78		120.78	96.62	24.16	
32	sq.m.	3	1	1	204	53.83	16.71	70.54	120.78	NA	120.78		120.78	96.62	24.16	
32	sq.m.	3	2	1	101	86.12	26.73	112.85	193.22	NA	193.22		193.22	154.58	38.64	
32	sq.m.	4	1	1	101	129.18	40.09	169.27	289.82	NA	289.82		289.82	231.86	57.96	
32	sq.m.	4	2	1	301	1811.1	562.07	2373.17	4063.34	1628.64	1628.64	54792.03	60880.03	48704.03	12176.01	14.98
38	sq.m.	1	1	1	132	594.44	184.48	778.92	1333.67	NA	1333.67		1333.67	1066.93	266.73	
38	sq.m.	1	2	0	401	21.53	6.68	28.21	48.30	7.06	7.06	7.06	7.84	6.27	1.57	0.16
38	sq.m.	2	1	1	401	53.83	16.71	70.54	120.78	7.06	7.06	17.65	19.61	15.69	3.92	0.16
38	sq.m.	2	2	1	132	971	301.34	1272.34	2178.50	NA	2178.50		2178.50	1742.80	435.70	
38	sq.m.	3	1	1	401	107.65	33.41	141.06	241.52	7.06	7.06	35.29	39.22	31.37	7.84	0.16
38	sq.m.	3	2	1	132	1202.77	373.27	1576.04	2698.50	NA	2698.50		2698.50	2158.80	539.70	
38	sq.m.	4	1	1	401	215.3	66.82	282.12	483.05	7.06	7.06	70.59	78.43	62.74	15.69	0.16
38	sq.m.	4	2	1	132	1811.1	562.07	2373.17	4063.34	NA	4063.34		4063.34	3250.67	812.67	
38	sq.m.	5	1	1	132	1911.86	593.34	2505.2	4289.40	NA	4289.40		4289.40	3431.52	857.88	
38	sq.m.	5	2	1	101	322.95	100.23	423.18	724.57	NA	724.57		724.57	579.66	144.91	
39	sq.m.	1	1	0	401	0	0	0	0.00	7.06	7.06	0.00	0.00	0.00	0.00	
39	sq.m.	2	1	1	301	53.83	16.71	70.54	120.78	1628.64	1628.64	1628.64	1809.60	1447.68	361.92	14.98
39	sq.m.	3	1	1	301	107.65	33.41	141.06	241.52	1628.64	1628.64	3256.81	3618.68	2894.94	723.74	14.98
39	sq.m.	3	2	1	201	406.92	126.29	533.21	912.96	NA	912.96		912.96	730.37	182.59	
39	sq.m.	4	1	1	301	215.3	66.82	282.12	483.05	1628.64	1628.64	6513.62	7237.36	5789.88	1447.47	14.98
39	sq.m.	4	2	1	201	406.92	126.29	533.21	912.96	NA	912.96		912.96	730.37	182.59	
39	sq.m.	5	1	1	201	406.92	126.29	533.21	912.96	NA	912.96		912.96	730.37	182.59	
39	sq.m.	5	2	1	101	333.72	103.57	437.29	748.73	NA	748.73		748.73	598.98	149.75	
54	sq.m.	1	1	0	401	53.83	16.71	70.54	120.78	7.06	7.06	17.65	19.61	15.69	3.92	0.16
54	sq.m.	2	1	1	204	6.46	2	8.46	14.49	NA	14.49		14.49	11.59	2.90	
54	sq.m.	3	1	1	204	0	0	0	0.00	NA	0.00		0.00	0.00	0.00	
54	sq.m.	3	2	1	101	10.77	3.34	14.11	24.16	NA	24.16		24.16	19.33	4.83	
54	sq.m.	4	1	1	101	10.77	3.34	14.11	24.16	NA	24.16		24.16	19.33	4.83	
54	sq.m.	4	2	1	301	236.83	73.5	310.33	531.35	1628.64	1628.64	7164.94	7961.04	6368.83	1592.21	14.98
55	sq.m.	1	1	0	401	107.65	33.41	141.06	241.52	7.06	7.06	35.29	39.22	31.37	7.84	0.16
55	sq.m.	2	1	1	401	215.3	66.82	282.12	483.05	7.06	7.06	70.59	78.43	62.74	15.69	0.16
55	sq.m.	2	2	1	204	21.53	6.68	28.21	48.30	NA	48.30		48.30	38.64	9.66	
55	sq.m.	3	1	1	204	0	0	0	0.00	NA	0.00		0.00	0.00	0.00	
55	sq.m.	3	2	1	101	32.3	10.02	42.32	72.46	NA	72.46		72.46	57.97	14.49	
55	sq.m.	4	1	1	101	32.3	10.02	42.32	72.46	NA	72.46		72.46	57.97	14.49	
55	sq.m.	4	2	1	301	236.83	73.5	310.33	531.35	1628.64	1628.64	7164.94	7961.04	6368.83	1592.21	14.98

Table 5.25. Complete list of updated unit costs for Pontis element actions (continued)

elemkey	metricunit	skey	akey	wholeflag	asubcat	varunitco	fixunitco	Cost2001	ExistCost2009	Cost2009	AdjCost2009	AdjElemCost2009	ElemCost2009	varunitco2009	fixunitco2009	Change
98	sq.m.	1	1	1	201	406.92	126.29	533.21	912.96	NA	912.96		912.96	730.37	182.59	
98	sq.m.	1	2	0	403	21.53	6.68	28.21	48.30	NA	48.30		48.30	38.64	9.66	
98	sq.m.	2	1	1	401	53.83	16.71	70.54	120.78	7.06	7.06	17.65	19.61	15.69	3.92	0.16
98	sq.m.	2	2	1	132	129.18	40.09	169.27	289.82	NA	289.82		289.82	231.86	57.96	
98	sq.m.	3	1	1	401	107.65	33.41	141.06	241.52	7.06	7.06	35.29	39.22	31.37	7.84	0.16
98	sq.m.	3	2	1	301	129.18	40.09	169.27	289.82	1628.64	1628.64	3908.13	4342.36	3473.89	868.47	14.98
98	sq.m.	4	1	1	401	215.3	66.82	282.12	483.05	7.06	7.06	70.59	78.43	62.74	15.69	0.16
98	sq.m.	4	2	1	301	236.83	73.5	310.33	531.35	1628.64	1628.64	7164.94	7961.04	6368.83	1592.21	14.98
98	sq.m.	5	1	1	301	269.13	83.52	352.65	603.81	1628.64	1628.64	8142.03	9046.69	7237.36	1809.34	14.98
98	sq.m.	5	2	1	101	322.95	100.23	423.18	724.57	NA	724.57		724.57	579.66	144.91	
99	sq.m.	1	1	0	403	21.53	6.68	28.21	48.30	NA	48.30		48.30	38.64	9.66	
99	sq.m.	2	1	1	401	53.83	16.71	70.54	120.78	7.06	7.06	17.65	19.61	15.69	3.92	0.16
99	sq.m.	3	1	1	401	107.65	33.41	141.06	241.52	7.06	7.06	35.29	39.22	31.37	7.84	0.16
99	sq.m.	3	2	1	301	139.95	43.43	183.38	313.98	1628.64	1628.64	4233.90	4704.33	3763.47	940.87	14.98
99	sq.m.	4	1	1	401	236.83	73.5	310.33	531.35	7.06	7.06	77.65	86.27	69.02	17.25	0.16
99	sq.m.	4	2	1	301	269.13	83.52	352.65	603.81	1628.64	1628.64	8142.03	9046.69	7237.36	1809.34	14.98
99	sq.m.	5	1	1	301	366.01	113.59	479.6	821.17	1628.64	1628.64	11073.06	12303.40	9842.72	2460.68	14.98
99	sq.m.	5	2	1	101	333.72	103.57	437.29	748.73	NA	748.73		748.73	598.98	149.75	
101	m.	1	1	0	402	82.03	27.34	109.37	187.26	NA	187.26		187.26	149.81	37.45	
101	m.	2	1	0	302	11942.84	3980.95	15923.79	27264.71	NA	27264.71		27264.71	21811.77	5452.94	
101	m.	3	1	0	302	11942.84	3980.95	15923.79	27264.71	NA	27264.71		27264.71	21811.77	5452.94	
101	m.	4	1	0	202	65620	21873.33	87493.33	149806.08	NA	149806.08		149806.08	119844.86	29961.22	
101	m.	4	2	0	142	4921.5	1275.94	6197.44	10611.26	NA	10611.26		10611.26	8489.01	2122.25	
102	m.	1	1	0	400	32.81	8.51	41.32	70.75	19.56	19.56	114.63	127.37	101.89	25.47	1.80
102	m.	1	2	0	402	82.03	27.34	109.37	187.26	NA	187.26		187.26	149.81	37.45	
102	m.	2	1	0	400	32.81	8.51	41.32	70.75	19.56	19.56	114.63	127.37	101.89	25.47	1.80
102	m.	2	2	0	302	11942.84	3980.95	15923.79	27264.71	NA	27264.71		27264.71	21811.77	5452.94	
102	m.	3	1	0	302	13780.2	4593.4	18373.6	31459.28	NA	31459.28		31459.28	25167.42	6291.86	
102	m.	4	1	0	302	13780.2	4593.4	18373.6	31459.28	NA	31459.28		31459.28	25167.42	6291.86	
102	m.	4	2	0	102	9186.8	3062.27	12249.07	20972.86	327.63	327.63	36693.60	40770.67	32616.53	8154.13	1.94
102	m.	5	1	0	202	65620	21873.33	87493.33	149806.08	NA	149806.08		149806.08	119844.86	29961.22	
102	m.	5	2	0	142	4921.5	1275.94	6197.44	10611.26	NA	10611.26		10611.26	8489.01	2122.25	
104	m.	1	1	0	403	82.03	21.27	103.3	176.87	NA	176.87		176.87	141.50	35.37	
104	m.	2	1	0	403	131.24	34.03	165.27	282.98	NA	282.98		282.98	226.38	56.60	
104	m.	3	1	0	303	3281	850.63	4131.63	7074.18	606.88	606.88	4045.91	4495.46	3596.37	899.09	0.64
104	m.	4	1	0	203	1640.5	425.31	2065.81	3537.08	NA	3537.08		3537.08	2829.66	707.42	
104	m.	4	2	0	142	9843	2551.89	12394.89	21222.53	NA	21222.53		21222.53	16978.02	4244.51	
105	m.	1	1	0	403	114.84	29.77	144.61	247.60	NA	247.60		247.60	198.08	49.52	
105	m.	2	1	0	403	147.65	38.28	185.93	318.35	NA	318.35		318.35	254.68	63.67	
105	m.	3	1	0	303	3281	850.63	4131.63	7074.18	606.88	606.88	4045.91	4495.46	3596.37	899.09	0.64
105	m.	4	1	0	203	1640.5	425.31	2065.81	3537.08	NA	3537.08		3537.08	2829.66	707.42	
105	m.	4	2	0	142	2001.41	518.88	2520.29	4315.24	NA	4315.24		4315.24	3452.19	863.05	
106	m.	1	1	0	402	82.03	27.34	109.37	187.26	NA	187.26		187.26	149.81	37.45	
106	m.	2	1	0	302	223.11	74.37	297.48	509.35	NA	509.35		509.35	407.48	101.87	
106	m.	3	1	0	302	223.11	74.37	297.48	509.35	NA	509.35		509.35	407.48	101.87	
106	m.	4	1	0	202	19686	6562	26248	44941.83	NA	44941.83		44941.83	35953.46	8988.37	
106	m.	4	2	0	141	2952.9	765.57	3718.47	6366.76	963.93	963.93	7610.07	8455.63	6764.51	1691.13	1.33

Table 5.25. Complete list of updated unit costs for Pontis element actions (continued)

elemkey	metricunit	skey	akey	wholeflag	asubcat	varunitco	fixunitco	Cost2001	ExistCost2009	Cost2009	AdjCost2009	AdjElemCost2009	ElemCost2009	varunitco2009	fixunitco2009	Change
107	m.	1	1	0	400	32.81	8.51	41.32	70.75	19.56	19.56	114.63	127.37	101.89	25.47	1.80
107	m.	1	2	0	402	82.03	27.34	109.37	187.26	NA	187.26		187.26	149.81	37.45	
107	m.	2	1	0	400	32.81	8.51	41.32	70.75	19.56	19.56	114.63	127.37	101.89	25.47	1.80
107	m.	2	2	0	302	223.11	74.37	297.48	509.35	NA	509.35		509.35	407.48	101.87	
107	m.	3	1	0	302	255.92	85.31	341.23	584.25	NA	584.25		584.25	467.40	116.85	
107	m.	4	1	0	302	255.92	85.31	341.23	584.25	NA	584.25		584.25	467.40	116.85	
107	m.	4	2	0	102	170.61	56.87	227.48	389.49	327.63	327.63	681.44	757.16	605.73	151.43	1.94
107	m.	5	1	0	202	19686	6562	26248	44941.83	NA	44941.83		44941.83	35953.46	8988.37	
107	m.	5	2	0	141	2952.9	765.57	3718.47	6366.76	963.93	963.93	7610.07	8455.63	6764.51	1691.13	1.33
109	m.	1	1	0	403	114.84	29.77	144.61	247.60	NA	247.60		247.60	198.08	49.52	
109	m.	2	1	0	403	147.65	38.28	185.93	318.35	NA	318.35		318.35	254.68	63.67	
109	m.	3	1	0	303	656.2	170.13	826.33	1414.84	606.88	606.88	809.19	899.10	719.28	179.82	0.64
109	m.	4	1	0	203	1640.5	425.31	2065.81	3537.08	NA	3537.08		3537.08	2829.66	707.42	
109	m.	4	2	0	141	1213.97	314.73	1528.7	2617.44	963.93	963.93	3128.57	3476.19	2780.96	695.24	1.33
110	m.	1	1	0	403	82.03	21.27	103.3	176.87	NA	176.87		176.87	141.50	35.37	
110	m.	2	1	0	403	147.65	38.28	185.93	318.35	NA	318.35		318.35	254.68	63.67	
110	m.	3	1	0	303	656.2	170.13	826.33	1414.84	606.88	606.88	809.19	899.10	719.28	179.82	0.64
110	m.	4	1	0	203	1640.5	425.31	2065.81	3537.08	NA	3537.08		3537.08	2829.66	707.42	
110	m.	4	2	0	141	1213.97	314.73	1528.7	2617.44	963.93	963.93	3128.57	3476.19	2780.96	695.24	1.33
111	m.	1	1	0	404	82.03	21.27	103.3	176.87	NA	176.87		176.87	141.50	35.37	
111	m.	2	1	0	204	295.29	76.56	371.85	636.68	NA	636.68		636.68	509.35	127.34	
111	m.	3	1	0	204	295.29	76.56	371.85	636.68	NA	636.68		636.68	509.35	127.34	
111	m.	3	2	0	141	492.15	127.59	619.74	1061.12	963.93	963.93	1268.33	1409.26	1127.41	281.85	1.33
111	m.	4	1	0	204	295.29	76.56	371.85	636.68	NA	636.68		636.68	509.35	127.34	
111	m.	4	2	0	141	492.15	127.59	619.74	1061.12	963.93	963.93	1268.33	1409.26	1127.41	281.85	1.33
112	m.	1	1	0	402	82.03	27.34	109.37	187.26	NA	187.26		187.26	149.81	37.45	
112	m.	2	1	0	302	141.08	47.03	188.11	322.08	NA	322.08		322.08	257.67	64.42	
112	m.	3	1	0	302	141.08	47.03	188.11	322.08	NA	322.08		322.08	257.67	64.42	
112	m.	4	1	0	202	13124	4374.67	17498.67	29961.22	NA	29961.22		29961.22	23968.98	5992.24	
112	m.	4	2	0	141	689.01	178.63	867.64	1485.57	963.93	963.93	1775.68	1972.97	1578.38	394.59	1.33
113	m.	1	1	0	400	32.81	8.51	41.32	70.75	19.56	19.56	114.63	127.37	101.89	25.47	1.80
113	m.	1	2	0	402	82.03	27.34	109.37	187.26	NA	187.26		187.26	149.81	37.45	
113	m.	2	1	0	400	32.81	8.51	41.32	70.75	19.56	19.56	114.63	127.37	101.89	25.47	1.80
113	m.	2	2	0	302	141.08	47.03	188.11	322.08	NA	322.08		322.08	257.67	64.42	
113	m.	3	1	0	302	164.05	54.68	218.73	374.51	NA	374.51		374.51	299.61	74.90	
113	m.	4	1	0	302	164.05	54.68	218.73	374.51	NA	374.51		374.51	299.61	74.90	
113	m.	4	2	0	102	108.27	36.09	144.36	247.17	327.63	327.63	432.45	480.50	384.40	96.10	1.94
113	m.	5	1	0	202	13124	4374.67	17498.67	29961.22	NA	29961.22		29961.22	23968.98	5992.24	
113	m.	5	2	0	141	689.01	178.63	867.64	1485.57	963.93	963.93	1775.68	1972.97	1578.38	394.59	1.33
116	m.	1	1	0	403	114.84	29.77	144.61	247.60	NA	247.60		247.60	198.08	49.52	
116	m.	2	1	0	403	147.65	38.28	185.93	318.35	NA	318.35		318.35	254.68	63.67	
116	m.	3	1	0	303	656.2	170.13	826.33	1414.84	606.88	606.88	809.19	899.10	719.28	179.82	0.64
116	m.	4	1	0	203	1640.5	425.31	2065.81	3537.08	NA	3537.08		3537.08	2829.66	707.42	
116	m.	4	2	0	141	885.87	229.67	1115.54	1910.03	963.93	963.93	2283.02	2536.69	2029.35	507.34	1.33

Table 5.25. Complete list of updated unit costs for Pontis element actions (continued)

elemkey	metricunit	skey	akey	wholeflag	asubcat	varunitco	fixunitco	Cost2001	ExistCost2009	Cost2009	AdjCost2009	AdjElemCost2009	ElemCost2009	varunitco2009	fixunitco2009	Change
117	m.	1	1	0	404	82.03	21.27	103.3	176.87	NA	176.87		176.87	141.50	35.37	
117	m.	2	1	0	204	223.11	57.84	280.95	481.04	NA	481.04		481.04	384.83	96.21	
117	m.	3	1	0	204	223.11	57.84	280.95	481.04	NA	481.04		481.04	384.83	96.21	
117	m.	3	2	0	141	374.03	96.97	471	806.45	963.93	963.93	963.93	1071.03	856.83	214.21	1.33
117	m.	4	1	0	204	223.11	57.84	280.95	481.04	NA	481.04		481.04	384.83	96.21	
117	m.	4	2	0	141	374.03	96.97	471	806.45	963.93	963.93	963.93	1071.03	856.83	214.21	1.33
120	m.	1	1	0	402	82.03	27.34	109.37	187.26	NA	187.26		187.26	149.81	37.45	
120	m.	2	1	0	302	501.99	167.33	669.32	1146.01	NA	1146.01		1146.01	916.81	229.20	
120	m.	3	1	0	302	501.99	167.33	669.32	1146.01	NA	1146.01		1146.01	916.81	229.20	
120	m.	4	1	0	202	98430	32810	131240	224709.13	NA	224709.13		224709.13	179767.30	44941.83	
120	m.	4	2	0	142	2624.8	680.5	3305.3	5659.33	NA	5659.33		5659.33	4527.47	1131.87	
121	m.	1	1	0	400	32.81	8.51	41.32	70.75	19.56	19.56	114.63	127.37	101.89	25.47	1.80
121	m.	1	2	0	402	82.03	27.34	109.37	187.26	NA	187.26		187.26	149.81	37.45	
121	m.	2	1	0	400	32.81	8.51	41.32	70.75	19.56	19.56	114.63	127.37	101.89	25.47	1.80
121	m.	2	2	0	302	501.99	167.33	669.32	1146.01	NA	1146.01		1146.01	916.81	229.20	
121	m.	3	1	0	302	580.74	193.58	774.32	1325.79	NA	1325.79		1325.79	1060.63	265.16	
121	m.	4	1	0	302	580.74	193.58	774.32	1325.79	NA	1325.79		1325.79	1060.63	265.16	
121	m.	4	2	0	102	387.16	129.05	516.21	883.85	327.63	327.63	1546.37	1718.19	1374.55	343.64	1.94
121	m.	5	1	0	202	98430	32810	131240	224709.13	NA	224709.13		224709.13	179767.30	44941.83	
121	m.	5	2	0	142	2624.8	680.5	3305.3	5659.33	NA	5659.33		5659.33	4527.47	1131.87	
125	m.	1	1	0	402	82.03	27.34	109.37	187.26	NA	187.26		187.26	149.81	37.45	
125	m.	2	1	0	302	639.8	213.27	853.07	1460.63	NA	1460.63		1460.63	1168.50	292.13	
125	m.	3	1	0	302	639.8	213.27	853.07	1460.63	NA	1460.63		1460.63	1168.50	292.13	
125	m.	4	1	0	202	98430	32810	131240	224709.13	NA	224709.13		224709.13	179767.30	44941.83	
125	m.	4	2	0	142	2952.9	765.57	3718.47	6366.76	NA	6366.76		6366.76	5093.41	1273.35	
126	m.	1	1	0	400	32.81	8.51	41.32	70.75	19.56	19.56	114.63	127.37	101.89	25.47	1.80
126	m.	1	2	0	402	82.03	27.34	109.37	187.26	NA	187.26		187.26	149.81	37.45	
126	m.	2	1	0	400	32.81	8.51	41.32	70.75	19.56	19.56	114.63	127.37	101.89	25.47	1.80
126	m.	2	2	0	302	639.8	213.27	853.07	1460.63	NA	1460.63		1460.63	1168.50	292.13	
126	m.	3	1	0	302	738.23	246.08	984.31	1685.34	NA	1685.34		1685.34	1348.27	337.07	
126	m.	4	1	0	302	738.23	246.08	984.31	1685.34	NA	1685.34		1685.34	1348.27	337.07	
126	m.	4	2	0	102	492.15	164.05	656.2	1123.55	327.63	327.63	1965.73	2184.14	1747.31	436.83	1.94
126	m.	5	1	0	202	98430	32810	131240	224709.13	NA	224709.13		224709.13	179767.30	44941.83	
126	m.	5	2	0	142	3116.95	808.1	3925.05	6720.47	NA	6720.47		6720.47	5376.38	1344.09	
131	m.	1	1	0	400	32.81	8.51	41.32	70.75	19.56	19.56	114.63	127.37	101.89	25.47	1.80
131	m.	1	2	0	402	82.03	27.34	109.37	187.26	NA	187.26		187.26	149.81	37.45	
131	m.	2	1	0	400	32.81	8.51	41.32	70.75	19.56	19.56	114.63	127.37	101.89	25.47	1.80
131	m.	2	2	0	302	2985.71	995.24	3980.95	6816.18	NA	6816.18		6816.18	5452.95	1363.24	
131	m.	3	1	0	302	3445.05	1148.35	4593.4	7864.82	NA	7864.82		7864.82	6291.86	1572.96	
131	m.	4	1	0	302	3445.05	1148.35	4593.4	7864.82	NA	7864.82		7864.82	6291.86	1572.96	
131	m.	4	2	0	102	2296.7	765.57	3062.27	5243.22	327.63	327.63	9173.41	10192.68	8154.14	2038.54	1.94
131	m.	5	1	0	202	82025	27341.67	109366.67	187257.61	NA	187257.61		187257.61	149806.09	37451.52	
131	m.	5	2	0	142	2952.9	765.57	3718.47	6366.76	NA	6366.76		6366.76	5093.41	1273.35	

Table 5.25. Complete list of updated unit costs for Pontis element actions (continued)

elemkey	metricunit	skey	akey	wholeflag	asubcat	varunitco	fixunitco	Cost2001	ExistCost2009	Cost2009	AdjCost2009	AdjElemCost2009	ElemCost2009	varunitco2009	fixunitco2009	Change
135	m.	1	1	0	404	82.03	21.27	103.3	176.87	NA	176.87		176.87	141.50	35.37	
135	m.	2	1	0	204	1378.02	357.26	1735.28	2971.15	NA	2971.15		2971.15	2376.92	594.23	
135	m.	3	1	0	204	1378.02	357.26	1735.28	2971.15	NA	2971.15		2971.15	2376.92	594.23	
135	m.	3	2	0	142	2296.7	595.44	2892.14	4951.92	NA	4951.92		4951.92	3961.54	990.38	
135	m.	4	1	0	204	1378.02	357.26	1735.28	2971.15	NA	2971.15		2971.15	2376.92	594.23	
135	m.	4	2	0	142	2624.8	680.5	3305.3	5659.33	NA	5659.33		5659.33	4527.47	1131.87	
140	m.	1	1	0	402	82.03	27.34	109.37	187.26	NA	187.26		187.26	149.81	37.45	
140	m.	2	1	0	302	1804.55	601.52	2406.07	4119.67	NA	4119.67		4119.67	3295.74	823.93	
140	m.	3	1	0	302	1804.55	601.52	2406.07	4119.67	NA	4119.67		4119.67	3295.74	823.93	
140	m.	4	1	0	202	82025	27341.67	109366.67	187257.61	NA	187257.61		187257.61	149806.09	37451.52	
140	m.	4	2	0	142	2952.9	765.57	3718.47	6366.76	NA	6366.76		6366.76	5093.41	1273.35	
141	m.	1	1	0	400	32.81	8.51	41.32	70.75	19.56	19.56	114.63	127.37	101.89	25.47	1.80
141	m.	1	2	0	402	82.03	27.34	109.37	187.26	NA	187.26		187.26	149.81	37.45	
141	m.	2	1	0	400	32.81	8.51	41.32	70.75	19.56	19.56	114.63	127.37	101.89	25.47	1.80
141	m.	2	2	0	302	1804.55	601.52	2406.07	4119.67	NA	4119.67		4119.67	3295.74	823.93	
141	m.	3	1	0	302	2067.03	689.01	2756.04	4718.89	NA	4718.89		4718.89	3775.11	943.78	
141	m.	4	1	0	302	2067.03	689.01	2756.04	4718.89	NA	4718.89		4718.89	3775.11	943.78	
141	m.	4	2	0	102	1378.02	459.34	1837.36	3145.93	327.63	327.63	5504.04	6115.60	4892.48	1223.12	1.94
141	m.	5	1	0	202	82025	27341.67	109366.67	187257.61	NA	187257.61		187257.61	149806.09	37451.52	
141	m.	5	2	0	142	2952.9	765.57	3718.47	6366.76	NA	6366.76		6366.76	5093.41	1273.35	
143	m.	1	1	0	403	114.84	29.77	144.61	247.60	NA	247.60		247.60	198.08	49.52	
143	m.	2	1	0	403	147.65	38.28	185.93	318.35	NA	318.35		318.35	254.68	63.67	
143	m.	3	1	0	303	656.2	170.13	826.33	1414.84	606.88	606.88	809.19	899.10	719.28	179.82	0.64
143	m.	4	1	0	203	1640.5	425.31	2065.81	3537.08	NA	3537.08		3537.08	2829.66	707.42	
143	m.	4	2	0	142	574.18	148.86	723.04	1237.99	NA	1237.99		1237.99	990.39	247.60	
144	m.	1	1	0	403	82.03	21.27	103.3	176.87	NA	176.87		176.87	141.50	35.37	
144	m.	2	1	0	403	147.65	38.28	185.93	318.35	NA	318.35		318.35	254.68	63.67	
144	m.	3	1	0	303	656.2	170.13	826.33	1414.84	606.88	606.88	809.19	899.10	719.28	179.82	0.64
144	m.	4	1	0	203	1640.5	425.31	2065.81	3537.08	NA	3537.08		3537.08	2829.66	707.42	
144	m.	4	2	0	142	5577.7	1446.07	7023.77	12026.10	NA	12026.10		12026.10	9620.88	2405.22	
146	ea.	1	1	0	402	5000	1666.67	6666.67	11414.67	NA	11414.67		11414.67	9131.74	2282.93	
146	ea.	2	1	0	302	7500	2500	10000	17122.00	NA	17122.00		17122.00	13697.60	3424.40	
146	ea.	3	1	0	302	10000	3333.33	13333.33	22829.33	NA	22829.33		22829.33	18263.46	4565.87	
146	ea.	4	1	0	243	120000	31111.11	151111.11	258732.44	NA	258732.44		258732.44	206985.95	51746.49	
146	ea.	4	2	0	143	160000	41481.48	201481.48	344976.59	NA	344976.59		344976.59	275981.27	68995.32	
147	ea.	1	1	0	402	5000	1666.67	6666.67	11414.67	NA	11414.67		11414.67	9131.74	2282.93	
147	ea.	2	1	0	402	7500	2500	10000	17122.00	NA	17122.00		17122.00	13697.60	3424.40	
147	ea.	3	1	0	402	10000	3333.33	13333.33	22829.33	NA	22829.33		22829.33	18263.46	4565.87	
147	ea.	4	1	0	243	120000	31111.11	151111.11	258732.44	NA	258732.44		258732.44	206985.95	51746.49	
147	ea.	4	2	0	143	160000	41481.48	201481.48	344976.59	NA	344976.59		344976.59	275981.27	68995.32	
147	ea.	5	1	0	243	120000	31111.11	151111.11	258732.44	NA	258732.44		258732.44	206985.95	51746.49	
147	ea.	5	2	0	143	160000	41481.48	201481.48	344976.59	NA	344976.59		344976.59	275981.27	68995.32	

Table 5.25. Complete list of updated unit costs for Pontis element actions (continued)

elemkey	metricunit	skey	akey	wholeflag	asubcat	varunitco	fixunitco	Cost2001	ExistCost2009	Cost2009	AdjCost2009	AdjElemCost2009	ElemCost2009	varunitco2009	fixunitco2009	Change
151	m.	1	1	0	402	82.03	27.34	109.37	187.26	NA	187.26		187.26	149.81	37.45	
151	m.	2	1	0	302	229.67	76.56	306.23	524.33	NA	524.33		524.33	419.46	104.87	
151	m.	3	1	0	302	229.67	76.56	306.23	524.33	NA	524.33		524.33	419.46	104.87	
151	m.	4	1	0	202	13124	4374.67	17498.67	29961.22	NA	29961.22		29961.22	23968.98	5992.24	
151	m.	4	2	0	141	1509.26	391.29	1900.55	3254.12	963.93	963.93	3889.59	4321.76	3457.41	864.35	1.33
152	m.	1	1	0	400	32.81	8.51	41.32	70.75	19.56	19.56	114.63	127.37	101.89	25.47	1.80
152	m.	1	2	0	402	82.03	27.34	109.37	187.26	NA	187.26		187.26	149.81	37.45	
152	m.	2	1	0	400	32.81	8.51	41.32	70.75	19.56	19.56	114.63	127.37	101.89	25.47	1.80
152	m.	2	2	0	302	229.67	76.56	306.23	524.33	NA	524.33		524.33	419.46	104.87	
152	m.	3	1	0	302	265.76	88.59	354.35	606.72	NA	606.72		606.72	485.37	121.34	
152	m.	4	1	0	302	265.76	88.59	354.35	606.72	NA	606.72		606.72	485.37	121.34	
152	m.	4	2	0	102	177.17	59.06	236.23	404.47	327.63	327.63	707.66	786.28	629.03	157.26	1.94
152	m.	5	1	0	202	13124	4374.67	17498.67	29961.22	NA	29961.22		29961.22	23968.98	5992.24	
152	m.	5	2	0	141	1509.26	391.29	1900.55	3254.12	963.93	963.93	3889.59	4321.76	3457.41	864.35	1.33
154	m.	1	1	0	403	114.84	29.77	144.61	247.60	NA	247.60		247.60	198.08	49.52	
154	m.	2	1	0	403	147.65	38.28	185.93	318.35	NA	318.35		318.35	254.68	63.67	
154	m.	3	1	0	303	656.2	170.13	826.33	1414.84	606.88	606.88	809.19	899.10	719.28	179.82	0.64
154	m.	4	1	0	203	1640.5	425.31	2065.81	3537.08	NA	3537.08		3537.08	2829.66	707.42	
154	m.	4	2	0	141	885.87	229.67	1115.54	1910.03	963.93	963.93	2283.02	2536.69	2029.35	507.34	1.33
155	m.	1	1	0	403	114.84	29.77	144.61	247.60	NA	247.60		247.60	198.08	49.52	
155	m.	2	1	0	403	147.65	38.28	185.93	318.35	NA	318.35		318.35	254.68	63.67	
155	m.	3	1	0	303	656.2	170.13	826.33	1414.84	606.88	606.88	809.19	899.10	719.28	179.82	0.64
155	m.	4	1	0	203	1640.5	425.31	2065.81	3537.08	NA	3537.08		3537.08	2829.66	707.42	
155	m.	4	2	0	141	885.87	229.67	1115.54	1910.03	963.93	963.93	2283.02	2536.69	2029.35	507.34	1.33
156	m.	1	1	0	404	82.03	21.27	103.3	176.87	NA	176.87		176.87	141.50	35.37	
156	m.	2	1	0	204	223.11	57.84	280.95	481.04	NA	481.04		481.04	384.83	96.21	
156	m.	3	1	0	204	223.11	57.84	280.95	481.04	NA	481.04		481.04	384.83	96.21	
156	m.	3	2	0	141	374.03	96.97	471	806.45	963.93	963.93	963.93	1071.03	856.83	214.21	1.33
156	m.	4	1	0	204	328.1	85.06	413.16	707.41	NA	707.41		707.41	565.93	141.48	
156	m.	4	2	0	141	374.03	96.97	471	806.45	963.93	963.93	963.93	1071.03	856.83	214.21	1.33
160	ea.	1	1	0	402	200	51.85	251.85	431.22	NA	431.22		431.22	344.97	86.24	
160	ea.	2	1	0	302	200	51.85	251.85	431.22	NA	431.22		431.22	344.97	86.24	
160	ea.	3	1	0	302	142	47.33	189.33	324.17	NA	324.17		324.17	259.34	64.83	
160	ea.	4	1	0	202	142	47.33	189.33	324.17	NA	324.17		324.17	259.34	64.83	
160	ea.	4	2	0	102	708	236	944	1616.32	327.63	327.63	2827.87	3142.08	2513.66	628.42	1.94
161	ea.	1	1	0	400	200	51.85	251.85	431.22	19.56	19.56	698.69	776.32	621.05	155.26	1.80
161	ea.	1	2	0	402	25	8.33	33.33	57.07	NA	57.07		57.07	45.65	11.41	
161	ea.	2	1	0	400	200	51.85	251.85	431.22	19.56	19.56	698.69	776.32	621.05	155.26	1.80
161	ea.	2	2	0	302	71	23.67	94.67	162.09	NA	162.09		162.09	129.68	32.42	
161	ea.	3	1	0	302	142	47.33	189.33	324.17	NA	324.17		324.17	259.34	64.83	
161	ea.	4	1	0	302	142	47.33	189.33	324.17	NA	324.17		324.17	259.34	64.83	
161	ea.	4	2	0	102	708	236	944	1616.32	327.63	327.63	2827.87	3142.08	2513.66	628.42	1.94
161	ea.	5	1	0	202	75000	25000	100000	171220.00	NA	171220.00		171220.00	136976.00	34244.00	
161	ea.	5	2	0	113	100000	25925.93	125925.93	215610.38	5769.86	5769.86	1923275.02	2136972.25	1709577.80	427394.45	9.91

Table 5.25. Complete list of updated unit costs for Pontis element actions (continued)

elemkey	metricunit	skey	akey	wholeflag	asubcat	varunitco	fixunitco	Cost2001	ExistCost2009	Cost2009	AdjCost2009	AdjElemCost2009	ElemCost2009	varunitco2009	fixunitco2009	Change
201	ea.	1	1	0	402	500	166.67	666.67	1141.47	NA	1141.47		1141.47	1027.33	114.15	
201	ea.	2	1	0	302	25	8.33	33.33	57.07	NA	57.07		57.07	51.36	5.71	
201	ea.	3	1	0	302	25	8.33	33.33	57.07	NA	57.07		57.07	51.36	5.71	
201	ea.	4	1	0	202	1000	333.33	1333.33	2282.93	NA	2282.93		2282.93	2054.63	228.29	
201	ea.	4	2	0	144	20000	5185.19	25185.19	43122.08	NA	43122.08		43122.08	38809.87	4312.21	
202	ea.	1	1	0	400	200	51.85	251.85	431.22	19.56	19.56	698.69	776.32	698.69	77.63	1.80
202	ea.	1	2	0	402	500	166.67	666.67	1141.47	NA	1141.47		1141.47	1027.33	114.15	
202	ea.	2	1	0	400	200	51.85	251.85	431.22	19.56	19.56	698.69	776.32	698.69	77.63	1.80
202	ea.	2	2	0	302	25	8.33	33.33	57.07	NA	57.07		57.07	51.36	5.71	
202	ea.	3	1	0	302	50	16.67	66.67	114.15	NA	114.15		114.15	102.74	11.42	
202	ea.	4	1	0	302	50	16.67	66.67	114.15	NA	114.15		114.15	102.74	11.42	
202	ea.	4	2	0	102	250	83.33	333.33	570.73	327.63	327.63	998.53	1109.48	998.53	110.95	1.94
202	ea.	5	1	0	202	1000	333.33	1333.33	2282.93	NA	2282.93		2282.93	2054.63	228.29	
202	ea.	5	2	0	144	20000	5185.19	25185.19	43122.08	NA	43122.08		43122.08	38809.87	4312.21	
204	ea.	1	1	0	403	500	129.63	629.63	1078.05	NA	1078.05		1078.05	970.25	107.81	
204	ea.	2	1	0	403	250	64.81	314.81	539.02	NA	539.02		539.02	485.12	53.90	
204	ea.	3	1	0	303	500	129.63	629.63	1078.05	606.88	606.88	616.57	685.07	616.57	68.51	0.64
204	ea.	4	1	0	203	5000	1296.3	6296.3	10780.52	NA	10780.52		10780.52	9702.47	1078.05	
204	ea.	4	2	0	144	20000	5185.19	25185.19	43122.08	NA	43122.08		43122.08	38809.87	4312.21	
205	ea.	1	1	0	403	500	129.63	629.63	1078.05	NA	1078.05		1078.05	970.25	107.81	
205	ea.	2	1	0	403	250	64.81	314.81	539.02	NA	539.02		539.02	485.12	53.90	
205	ea.	3	1	0	303	500	129.63	629.63	1078.05	606.88	606.88	616.57	685.07	616.57	68.51	0.64
205	ea.	4	1	0	203	5000	1296.3	6296.3	10780.52	NA	10780.52		10780.52	9702.47	1078.05	
205	ea.	4	2	0	144	20000	5185.19	25185.19	43122.08	NA	43122.08		43122.08	38809.87	4312.21	
206	ea.	1	1	0	404	100	25.93	125.93	215.62	NA	215.62		215.62	194.06	21.56	
206	ea.	2	1	0	204	600	155.56	755.56	1293.67	NA	1293.67		1293.67	1164.30	129.37	
206	ea.	3	1	0	204	600	155.56	755.56	1293.67	NA	1293.67		1293.67	1164.30	129.37	
206	ea.	3	2	0	144	1000	259.26	1259.26	2156.10	NA	2156.10		2156.10	1940.49	215.61	
206	ea.	4	1	0	204	600	155.56	755.56	1293.67	NA	1293.67		1293.67	1164.30	129.37	
206	ea.	4	2	0	144	1000	259.26	1259.26	2156.10	NA	2156.10		2156.10	1940.49	215.61	
207	ea.	1	1	0	403	500	129.63	629.63	1078.05	NA	1078.05		1078.05	970.25	107.81	
207	ea.	2	1	0	403	250	64.81	314.81	539.02	NA	539.02		539.02	485.12	53.90	
207	ea.	3	1	0	403	300	77.78	377.78	646.83	NA	646.83		646.83	582.15	64.68	
207	ea.	4	1	0	203	5000	1296.3	6296.3	10780.52	NA	10780.52		10780.52	9702.47	1078.05	
207	ea.	4	2	0	144	20000	5185.19	25185.19	43122.08	NA	43122.08		43122.08	38809.87	4312.21	
210	m.	1	1	0	403	98.43	25.52	123.95	212.23	NA	212.23		212.23	191.00	21.22	
210	m.	2	1	0	403	147.65	38.28	185.93	318.35	NA	318.35		318.35	286.51	31.83	
210	m.	3	1	0	303	1148.35	297.72	1446.07	2475.96	606.88	606.88	1416.07	1573.41	1416.07	157.34	0.64
210	m.	4	1	0	203	1640.5	425.31	2065.81	3537.08	NA	3537.08		3537.08	3183.37	353.71	
210	m.	4	2	0	144	9843	2551.89	12394.89	21222.53	NA	21222.53		21222.53	19100.28	2122.25	

Table 5.25. Complete list of updated unit costs for Pontis element actions (continued)

elemkey	metricunit	skey	akey	wholeflag	asubcat	varunitco	fixunitco	Cost2001	ExistCost2009	Cost2009	AdjCost2009	AdjElemCost2009	ElemCost2009	varunitco2009	fixunitco2009	Change
211	m.	1	1	0	405	82.03	21.27	103.3	176.87	NA	176.87		176.87	159.18	17.69	
211	m.	2	1	0	205	5905.8	1531.13	7436.93	12733.51	NA	12733.51		12733.51	11460.16	1273.35	
211	m.	3	1	0	205	5905.8	1531.13	7436.93	12733.51	NA	12733.51		12733.51	11460.16	1273.35	
211	m.	4	1	0	205	5905.8	1531.13	7436.93	12733.51	NA	12733.51		12733.51	11460.16	1273.35	
211	m.	4	2	0	144	9843	2551.89	12394.89	21222.53	NA	21222.53		21222.53	19100.28	2122.25	
215	m.	1	1	0	403	114.84	29.77	144.61	247.60	NA	247.60		247.60	222.84	24.76	
215	m.	2	1	0	403	147.65	38.28	185.93	318.35	NA	318.35		318.35	286.51	31.83	
215	m.	3	1	0	303	492.15	127.59	619.74	1061.12	606.88	606.88	606.88	674.31	606.88	67.43	0.64
215	m.	4	1	0	203	1640.5	425.31	2065.81	3537.08	NA	3537.08		3537.08	3183.37	353.71	
215	m.	4	2	0	144	2690.42	697.52	3387.94	5800.83	NA	5800.83		5800.83	5220.75	580.08	
216	m.	1	1	0	404	82.03	21.27	103.3	176.87	NA	176.87		176.87	159.18	17.69	
216	m.	2	1	0	204	1213.97	314.73	1528.7	2617.44	NA	2617.44		2617.44	2355.70	261.74	
216	m.	3	1	0	204	1213.97	314.73	1528.7	2617.44	NA	2617.44		2617.44	2355.70	261.74	
216	m.	3	2	0	144	2034.22	527.39	2561.61	4385.99	NA	4385.99		4385.99	3947.39	438.60	
216	m.	4	1	0	204	1213.97	314.73	1528.7	2617.44	NA	2617.44		2617.44	2355.70	261.74	
216	m.	4	2	0	144	2034.22	527.39	2561.61	4385.99	NA	4385.99		4385.99	3947.39	438.60	
217	m.	1	1	0	405	82.03	21.27	103.3	176.87	NA	176.87		176.87	159.18	17.69	
217	m.	2	1	0	205	1607.69	416.81	2024.5	3466.35	NA	3466.35		3466.35	3119.71	346.63	
217	m.	3	1	0	205	1607.69	416.81	2024.5	3466.35	NA	3466.35		3466.35	3119.71	346.63	
217	m.	4	1	0	205	1607.69	416.81	2024.5	3466.35	NA	3466.35		3466.35	3119.71	346.63	
217	m.	4	2	0	144	2690.42	697.52	3387.94	5800.83	NA	5800.83		5800.83	5220.75	580.08	
220	ea.	1	1	0	403	500	129.63	629.63	1078.05	NA	1078.05		1078.05	970.25	107.81	
220	ea.	2	1	0	403	250	64.81	314.81	539.02	NA	539.02		539.02	485.12	53.90	
220	ea.	3	1	0	303	500	129.63	629.63	1078.05	606.88	606.88	616.57	685.07	616.57	68.51	0.64
220	ea.	4	1	0	203	5000	1296.3	6296.3	10780.52	NA	10780.52		10780.52	9702.47	1078.05	
220	ea.	4	2	0	144	100000	25925.93	125925.93	215610.38	NA	215610.38		215610.38	194049.34	21561.04	
230	m.	1	1	0	402	82.03	27.34	109.37	187.26	NA	187.26		187.26	168.54	18.73	
230	m.	2	1	0	302	246.08	82.03	328.11	561.79	NA	561.79		561.79	505.61	56.18	
230	m.	3	1	0	302	246.08	82.03	328.11	561.79	NA	561.79		561.79	505.61	56.18	
230	m.	4	1	0	202	3281	1093.67	4374.67	7490.31	NA	7490.31		7490.31	6741.28	749.03	
230	m.	4	2	0	141	1509.26	391.29	1900.55	3254.12	963.93	963.93	3889.59	4321.76	3889.59	432.18	1.33
231	m.	1	1	0	400	32.81	8.51	41.32	70.75	19.56	19.56	114.63	127.37	114.63	12.74	1.80
231	m.	1	2	0	402	82.03	27.34	109.37	187.26	NA	187.26		187.26	168.54	18.73	
231	m.	2	1	0	400	32.81	8.51	41.32	70.75	19.56	19.56	114.63	127.37	114.63	12.74	1.80
231	m.	2	2	0	302	246.08	82.03	328.11	561.79	NA	561.79		561.79	505.61	56.18	
231	m.	3	1	0	302	285.45	95.15	380.6	651.66	NA	651.66		651.66	586.50	65.17	
231	m.	3	2	0	102	246.08	82.03	328.11	561.79	327.63	327.63	982.89	1092.10	982.89	109.21	1.94
231	m.	4	1	0	302	285.45	95.15	380.6	651.66	NA	651.66		651.66	586.50	65.17	
231	m.	4	2	0	102	190.3	63.43	253.73	434.44	327.63	327.63	760.08	844.53	760.08	84.45	1.94
231	m.	5	1	0	202	3281	1093.67	4374.67	7490.31	NA	7490.31		7490.31	6741.28	749.03	
231	m.	5	2	0	141	1509.26	391.29	1900.55	3254.12	963.93	963.93	3889.59	4321.76	3889.59	432.18	1.33
233	m.	1	1	0	403	114.84	29.77	144.61	247.60	NA	247.60		247.60	222.84	24.76	
233	m.	2	1	0	403	147.65	38.28	185.93	318.35	NA	318.35		318.35	286.51	31.83	
233	m.	3	1	0	303	656.2	170.13	826.33	1414.84	606.88	606.88	809.19	899.10	809.19	89.91	0.64
233	m.	4	1	0	203	1640.5	425.31	2065.81	3537.08	NA	3537.08		3537.08	3183.37	353.71	
233	m.	4	2	0	141	1509.26	391.29	1900.55	3254.12	963.93	963.93	3889.59	4321.76	3889.59	432.18	1.33

Table 5.25. Complete list of updated unit costs for Pontis element actions (continued)

elemkey	metricunit	skey	akey	wholeflag	asubcat	varunitco	fixunitco	Cost2001	ExistCost2009	Cost2009	AdjCost2009	AdjElemCost2009	ElemCost2009	varunitco2009	fixunitco2009	Change
234	m.	1	1	0	403	114.84	29.77	144.61	247.60	NA	247.60		247.60	222.84	24.76	
234	m.	2	1	0	403	147.65	38.28	185.93	318.35	NA	318.35		318.35	286.51	31.83	
234	m.	3	1	0	303	656.2	170.13	826.33	1414.84	606.88	606.88	809.19	899.10	809.19	89.91	0.64
234	m.	4	1	0	203	1640.5	425.31	2065.81	3537.08	NA	3537.08		3537.08	3183.37	353.71	
234	m.	4	2	0	141	1509.26	391.29	1900.55	3254.12	963.93	963.93	3889.59	4321.76	3889.59	432.18	1.33
235	m.	1	1	0	404	82.03	21.27	103.3	176.87	NA	176.87		176.87	159.18	17.69	
235	m.	2	1	0	204	295.29	76.56	371.85	636.68	NA	636.68		636.68	573.01	63.67	
235	m.	3	1	0	204	295.29	76.56	371.85	636.68	NA	636.68		636.68	573.01	63.67	
235	m.	3	2	0	141	492.15	127.59	619.74	1061.12	963.93	963.93	1268.33	1409.26	1268.33	140.93	1.33
235	m.	4	1	0	204	295.29	76.56	371.85	636.68	NA	636.68		636.68	573.01	63.67	
235	m.	4	2	0	141	492.15	127.59	619.74	1061.12	963.93	963.93	1268.33	1409.26	1268.33	140.93	1.33
240	m.	1	1	0	402	82.03	27.34	109.37	187.26	NA	187.26		187.26	149.81	37.45	
240	m.	2	1	0	202	4921.5	1640.5	6562	11235.46	NA	11235.46		11235.46	8988.37	2247.09	
240	m.	3	1	0	202	4921.5	1640.5	6562	11235.46	NA	11235.46		11235.46	8988.37	2247.09	
240	m.	4	1	0	202	4921.5	1640.5	6562	11235.46	NA	11235.46		11235.46	8988.37	2247.09	
240	m.	4	2	0	145	2559.18	731.19	3290.37	5633.77	NA	5633.77		5633.77	4507.02	1126.75	
241	m.	1	1	0	403	82.03	23.44	105.47	180.59	NA	180.59		180.59	144.47	36.12	
241	m.	2	1	0	203	984.3	281.23	1265.53	2166.84	NA	2166.84		2166.84	1733.47	433.37	
241	m.	3	1	0	203	2001.41	571.83	2573.24	4405.90	NA	4405.90		4405.90	3524.72	881.18	
241	m.	4	1	0	203	2985.71	853.06	3838.77	6572.74	NA	6572.74		6572.74	5258.19	1314.55	
241	m.	4	2	0	145	2362.32	674.95	3037.27	5200.41	NA	5200.41		5200.41	4160.33	1040.08	
242	m.	1	1	0	404	82.03	23.44	105.47	180.59	NA	180.59		180.59	144.47	36.12	
242	m.	2	1	0	204	738.23	210.92	949.15	1625.13	NA	1625.13		1625.13	1300.11	325.03	
242	m.	3	1	0	204	1509.26	431.22	1940.48	3322.49	NA	3322.49		3322.49	2657.99	664.50	
242	m.	4	1	0	204	2231.08	637.45	2868.53	4911.50	NA	4911.50		4911.50	3929.20	982.30	
242	m.	4	2	0	104	8858.7	2531.06	11389.76	19501.55	NA	19501.55		19501.55	15601.24	3900.31	
243	m.	1	1	0	405	82.03	23.44	105.47	180.59	NA	180.59		180.59	144.47	36.12	
243	m.	2	1	0	205	738.23	210.92	949.15	1625.13	NA	1625.13		1625.13	1300.11	325.03	
243	m.	3	1	0	205	1509.26	431.22	1940.48	3322.49	NA	3322.49		3322.49	2657.99	664.50	
243	m.	4	1	0	205	2231.08	637.45	2868.53	4911.50	NA	4911.50		4911.50	3929.20	982.30	
243	m.	4	2	0	145	8858.7	2531.06	11389.76	19501.55	NA	19501.55		19501.55	15601.24	3900.31	
290	ea.	1	1	0	422	500	115.38	615.38	1053.65	NA	1053.65		1053.65	948.29	105.37	
290	ea.	2	1	0	222	600	138.46	738.46	1264.39	NA	1264.39		1264.39	1137.95	126.44	
290	ea.	3	1	0	222	1000	230.77	1230.77	2107.32	NA	2107.32		2107.32	1896.59	210.73	
290	ea.	3	2	0	222	100000	23076.92	123076.92	210732.30	NA	210732.30		210732.30	189659.07	21073.23	
290	ea.	4	1	0	222	300000	69230.77	369230.77	632196.92	NA	632196.92		632196.92	568977.23	63219.69	
298	ea.	1	1	0	402	500	166.67	666.67	1141.47	NA	1141.47		1141.47	1027.33	114.15	
298	ea.	2	1	0	403	200	51.85	251.85	431.22	NA	431.22		431.22	388.10	43.12	
298	ea.	3	1	0	403	300	77.78	377.78	646.83	NA	646.83		646.83	582.15	64.68	
298	ea.	4	1	0	202	200	66.67	266.67	456.59	NA	456.59		456.59	410.93	45.66	
298	ea.	4	2	0	144	500	129.63	629.63	1078.05	NA	1078.05		1078.05	970.25	107.81	
299	ea.	1	1	0	402	500	166.67	666.67	1141.47	NA	1141.47		1141.47	1027.33	114.15	
299	ea.	2	1	0	403	200	51.85	251.85	431.22	NA	431.22		431.22	388.10	43.12	
299	ea.	3	1	0	303	500	129.63	629.63	1078.05	606.88	606.88	616.57	685.07	616.57	68.51	0.64
299	ea.	4	1	0	202	200	66.67	266.67	456.59	NA	456.59		456.59	410.93	45.66	
299	ea.	4	2	0	144	1000	259.26	1259.26	2156.10	NA	2156.10		2156.10	1940.49	215.61	

Table 5.25. Complete list of updated unit costs for Pontis element actions (continued)

elemkey	metricunit	skey	akey	wholeflag	asubcat	varunitco	fixunitco	Cost2001	ExistCost2009	Cost2009	AdjCost2009	AdjElemCost2009	ElemCost2009	varunitco2009	fixunitco2009	Change
300	m.	1	1	0	411	13.12	4.07	17.19	29.43	21.65	21.65	21.65	24.05	19.24	4.81	0.82
300	m.	2	1	0	311	200.14	62.11	262.25	449.02	213.41	213.41	433.91	482.12	385.70	96.42	1.07
300	m.	3	1	0	112	164.05	50.91	214.96	368.05	426.44	426.44	820.00	911.11	728.89	182.22	2.48
300	m.	3	2	0	111	400.28	124.22	524.5	898.05	264.15	264.15	264.15	293.50	234.80	58.70	0.33
301	m.	1	1	0	411	13.12	4.07	17.19	29.43	21.65	21.65	21.65	24.05	19.24	4.81	0.82
301	m.	2	1	0	112	85.31	26.48	111.79	191.41	426.44	426.44	426.44	473.82	379.06	94.76	2.48
301	m.	3	1	0	211	242.79	75.35	318.14	544.72	281.27	281.27	281.27	312.52	250.02	62.50	0.57
301	m.	3	2	0	111	400.28	124.22	524.5	898.05	264.15	264.15	264.15	293.50	234.80	58.70	0.33
302	m.	1	1	0	411	13.12	4.07	17.19	29.43	21.65	21.65	21.65	24.05	19.24	4.81	0.82
302	m.	2	1	0	311	98.43	30.55	128.98	220.84	213.41	213.41	213.41	237.12	189.69	47.42	1.07
302	m.	3	1	0	112	150.93	46.84	197.77	338.62	426.44	426.44	754.43	838.25	670.60	167.65	2.48
302	m.	3	2	0	111	498.71	154.77	653.48	1118.89	264.15	264.15	329.11	365.68	292.54	73.14	0.33
303	m.	1	1	0	411	13.12	4.07	17.19	29.43	21.65	21.65	21.65	24.05	19.24	4.81	0.82
303	m.	2	1	0	211	426.53	132.37	558.9	956.95	281.27	281.27	494.12	549.03	439.22	109.81	0.57
303	m.	3	1	0	211	623.39	193.47	816.86	1398.63	281.27	281.27	722.19	802.43	641.94	160.49	0.57
303	m.	3	2	0	111	1378.02	427.66	1805.68	3091.69	264.15	264.15	909.39	1010.43	808.35	202.09	0.33
304	m.	1	1	0	411	13.12	4.07	17.19	29.43	21.65	21.65	21.65	24.05	19.24	4.81	0.82
304	m.	2	1	0	211	262.48	81.46	343.94	588.89	281.27	281.27	304.08	337.86	270.29	67.57	0.57
304	m.	3	1	0	211	590.58	183.28	773.86	1325.00	281.27	281.27	684.17	760.19	608.15	152.04	0.57
304	m.	3	2	0	111	997.42	309.54	1306.96	2237.78	264.15	264.15	658.22	731.36	585.09	146.27	0.33
310	ea.	1	1	0	413	100	25.93	125.93	215.62	NA	215.62		215.62	172.49	43.12	
310	ea.	2	1	0	213	930	241.11	1171.11	2005.17	NA	2005.17		2005.17	1604.14	401.03	
310	ea.	3	1	0	213	930	241.11	1171.11	2005.17	NA	2005.17		2005.17	1604.14	401.03	
310	ea.	3	2	0	113	527	136.63	663.63	1136.27	5769.86	5769.86	10135.66	11261.85	9009.48	2252.37	9.91
311	ea.	1	1	0	413	100	25.93	125.93	215.62	NA	215.62		215.62	172.49	43.12	
311	ea.	2	1	0	302	720	240	960	1643.71	NA	1643.71		1643.71	1314.97	328.74	
311	ea.	3	1	0	213	900	233.33	1133.33	1940.49	NA	1940.49		1940.49	1552.39	388.10	
311	ea.	3	2	0	113	527	136.63	663.63	1136.27	5769.86	5769.86	10135.66	11261.85	9009.48	2252.37	9.91
312	ea.	1	1	0	413	100	25.93	125.93	215.62	NA	215.62		215.62	172.49	43.12	
312	ea.	2	1	0	213	1350	350	1700	2910.74	NA	2910.74		2910.74	2328.59	582.15	
312	ea.	3	1	0	213	3700	959.26	4659.26	7977.58	NA	7977.58		7977.58	6382.07	1595.52	
312	ea.	3	2	0	113	527	136.63	663.63	1136.27	5769.86	5769.86	10135.66	11261.85	9009.48	2252.37	9.91
313	ea.	1	1	0	413	100	25.93	125.93	215.62	NA	215.62		215.62	172.49	43.12	
313	ea.	2	1	0	213	670	173.7	843.7	1444.58	NA	1444.58		1444.58	1155.67	288.92	
313	ea.	3	1	0	213	1340	347.41	1687.41	2889.18	NA	2889.18		2889.18	2311.35	577.84	
313	ea.	3	2	0	113	527	136.63	663.63	1136.27	5769.86	5769.86	10135.66	11261.85	9009.48	2252.37	9.91
314	ea.	1	1	0	413	100	25.93	125.93	215.62	NA	215.62		215.62	172.49	43.12	
314	ea.	2	1	0	213	1500	388.89	1888.89	3234.16	NA	3234.16		3234.16	2587.33	646.83	
314	ea.	3	1	0	213	1500	388.89	1888.89	3234.16	NA	3234.16		3234.16	2587.33	646.83	
314	ea.	3	2	0	113	1800	466.67	2266.67	3880.99	5769.86	5769.86	34619.00	38465.56	30772.44	7693.11	9.91
315	ea.	1	1	0	413	90	23.33	113.33	194.04	NA	194.04		194.04	155.23	38.81	
315	ea.	2	1	0	213	90	23.33	113.33	194.04	NA	194.04		194.04	155.23	38.81	
315	ea.	3	1	0	213	150	38.89	188.89	323.42	NA	323.42		323.42	258.73	64.68	
315	ea.	3	2	0	113	300	77.78	377.78	646.83	5769.86	5769.86	5769.86	6410.95	5128.76	1282.19	9.91

Table 5.25. Complete list of updated unit costs for Pontis element actions (continued)

elemkey	metricunit	skey	akey	wholeflag	asubcat	varunitco	fixunitco	Cost2001	ExistCost2009	Cost2009	AdjCost2009	AdjElemCost2009	ElemCost2009	varunitco2009	fixunitco2009	Change
320	ea.	1	1	0	446	200	62.07	262.07	448.72	NA	448.72		448.72	358.97	89.74	
320	ea.	2	1	0	246	6000	1862.07	7862.07	13461.44	NA	13461.44		13461.44	10769.15	2692.29	
320	ea.	2	2	0	401	37.8	11.73	49.53	84.81	7.06	7.06	12.39	13.77	11.02	2.75	0.16
320	ea.	3	1	0	201	37.8	11.73	49.53	84.81	NA	84.81		84.81	67.84	16.96	
320	ea.	3	2	0	146	13000	4034.48	17034.48	29166.44	NA	29166.44		29166.44	23333.15	5833.29	
320	ea.	4	1	0	146	13000	4034.48	17034.48	29166.44	NA	29166.44		29166.44	23333.15	5833.29	
321	ea.	1	1	0	446	200	62.07	262.07	448.72	NA	448.72		448.72	358.97	89.74	
321	ea.	2	1	0	246	6000	1862.07	7862.07	13461.44	NA	13461.44		13461.44	10769.15	2692.29	
321	ea.	2	2	0	401	37.8	11.73	49.53	84.81	7.06	7.06	12.39	13.77	11.02	2.75	0.16
321	ea.	3	1	0	201	37.8	11.73	49.53	84.81	NA	84.81		84.81	67.84	16.96	
321	ea.	3	2	0	146	13000	4034.48	17034.48	29166.44	NA	29166.44		29166.44	23333.15	5833.29	
321	ea.	4	1	0	146	13000	4034.48	17034.48	29166.44	NA	29166.44		29166.44	23333.15	5833.29	
330	m.	1	1	0	402	82.03	27.34	109.37	187.26	NA	187.26		187.26	149.81	37.45	
330	m.	2	1	0	402	82.03	27.34	109.37	187.26	NA	187.26		187.26	149.81	37.45	
330	m.	3	1	0	402	82.03	27.34	109.37	187.26	NA	187.26		187.26	149.81	37.45	
330	m.	3	2	0	114	229.67	71.28	300.95	515.29	523.27	523.27	1093.45	1214.95	971.96	242.99	2.36
330	m.	4	1	0	202	423.25	141.08	564.33	966.25	NA	966.25		966.25	773.00	193.25	
330	m.	4	2	0	114	229.67	71.28	300.95	515.29	523.27	523.27	1093.45	1214.95	971.96	242.99	2.36
331	m.	1	1	0	403	114.84	35.64	150.48	257.65	NA	257.65		257.65	206.12	51.53	
331	m.	2	1	0	403	147.65	45.82	193.47	331.26	NA	331.26		331.26	265.01	66.25	
331	m.	3	1	0	303	656.2	203.65	859.85	1472.24	606.88	606.88	842.01	935.57	748.45	187.11	0.64
331	m.	4	1	0	203	1640.5	509.12	2149.62	3680.58	NA	3680.58		3680.58	2944.46	736.12	
331	m.	4	2	0	114	164.05	50.91	214.96	368.05	523.27	523.27	781.02	867.80	694.24	173.56	2.36
332	m.	1	1	0	404	82.03	25.46	107.49	184.04	NA	184.04		184.04	147.24	36.81	
332	m.	2	1	0	204	65.62	20.36	85.98	147.21	NA	147.21		147.21	117.77	29.44	
332	m.	3	1	0	114	109.91	34.11	144.02	246.59	523.27	523.27	523.27	581.41	465.13	116.28	2.36
333	m.	1	1	0	405	82.03	25.46	107.49	184.04	NA	184.04		184.04	147.24	36.81	
333	m.	2	1	0	205	147.65	45.82	193.47	331.26	NA	331.26		331.26	265.01	66.25	
333	m.	3	1	0	205	147.65	45.82	193.47	331.26	NA	331.26		331.26	265.01	66.25	
333	m.	3	2	0	114	196.86	61.09	257.95	441.66	523.27	523.27	937.22	1041.35	833.08	208.27	2.36
334	m.	1	1	0	402	82.03	27.34	109.37	187.26	NA	187.26		187.26	149.81	37.45	
334	m.	2	1	0	302	62.34	20.78	83.12	142.32	NA	142.32		142.32	113.85	28.46	
334	m.	3	1	0	302	95.15	31.72	126.87	217.23	NA	217.23		217.23	173.78	43.45	
334	m.	4	1	0	202	423.25	141.08	564.33	966.25	NA	966.25		966.25	773.00	193.25	
334	m.	4	2	0	114	229.67	71.28	300.95	515.29	523.27	523.27	1093.45	1214.95	971.96	242.99	2.36
334	m.	5	1	0	202	423.25	141.08	564.33	966.25	NA	966.25		966.25	773.00	193.25	
334	m.	5	2	0	114	229.67	71.28	300.95	515.29	523.27	523.27	1093.45	1214.95	971.96	242.99	2.36
386	m.	1	1	0	402	114.84	38.28	153.12	262.17	NA	262.17		262.17	235.95	26.22	
386	m.	2	1	0	302	147.65	49.22	196.87	337.08	NA	337.08		337.08	303.37	33.71	
386	m.	3	1	0	302	164.05	54.68	218.73	374.51	NA	374.51		374.51	337.06	37.45	
386	m.	4	1	0	202	1640.5	546.83	2187.33	3745.15	NA	3745.15		3745.15	3370.63	374.51	
386	m.	4	2	0	144	787.44	204.15	991.59	1697.80	NA	1697.80		1697.80	1528.02	169.78	

Table 5.25. Complete list of updated unit costs for Pontis element actions (continued)

elemkey	metricunit	skey	akey	wholeflag	asubcat	varunitco	fixunitco	Cost2001	ExistCost2009	Cost2009	AdjCost2009	AdjElemCost2009	ElemCost2009	varunitco2009	fixunitco2009	Change
387	m.	1	1	0	403	114.84	29.77	144.61	247.60	NA	247.60		247.60	222.84	24.76	
387	m.	2	1	0	403	147.65	38.28	185.93	318.35	NA	318.35		318.35	286.51	31.83	
387	m.	3	1	0	403	164.05	42.53	206.58	353.71	NA	353.71		353.71	318.34	35.37	
387	m.	4	1	0	203	1640.5	425.31	2065.81	3537.08	NA	3537.08		3537.08	3183.37	353.71	
387	m.	4	2	0	144	787.44	204.15	991.59	1697.80	NA	1697.80		1697.80	1528.02	169.78	
388	m.	1	1	0	403	82.03	21.27	103.3	176.87	NA	176.87		176.87	159.18	17.69	
388	m.	2	1	0	403	131.24	34.03	165.27	282.98	NA	282.98		282.98	254.68	28.30	
388	m.	3	1	0	403	164.05	42.53	206.58	353.71	NA	353.71		353.71	318.34	35.37	
388	m.	4	1	0	203	1640.5	425.31	2065.81	3537.08	NA	3537.08		3537.08	3183.37	353.71	
388	m.	4	2	0	144	787.44	204.15	991.59	1697.80	NA	1697.80		1697.80	1528.02	169.78	
389	m.	1	1	0	404	82.03	21.27	103.3	176.87	NA	176.87		176.87	159.18	17.69	
389	m.	2	1	0	204	472.46	122.49	594.95	1018.67	NA	1018.67		1018.67	916.81	101.87	
389	m.	3	1	0	204	472.46	122.49	594.95	1018.67	NA	1018.67		1018.67	916.81	101.87	
389	m.	3	2	0	144	472.46	122.49	594.95	1018.67	NA	1018.67		1018.67	916.81	101.87	
389	m.	4	1	0	204	472.46	122.49	594.95	1018.67	NA	1018.67		1018.67	916.81	101.87	
389	m.	4	2	0	144	787.44	204.15	991.59	1697.80	NA	1697.80		1697.80	1528.02	169.78	
390	m.	1	1	0	405	82.03	21.27	103.3	176.87	NA	176.87		176.87	159.18	17.69	
390	m.	2	1	0	205	656.2	170.13	826.33	1414.84	NA	1414.84		1414.84	1273.36	141.48	
390	m.	3	1	0	205	656.2	170.13	826.33	1414.84	NA	1414.84		1414.84	1273.36	141.48	
390	m.	3	2	0	144	787.44	204.15	991.59	1697.80	NA	1697.80		1697.80	1528.02	169.78	
390	m.	4	1	0	205	656.2	170.13	826.33	1414.84	NA	1414.84		1414.84	1273.36	141.48	
390	m.	4	2	0	144	787.44	204.15	991.59	1697.80	NA	1697.80		1697.80	1528.02	169.78	
393	m	1	1	0	402	269.13	89.71	358.84	614.41	NA	614.41		614.41	552.97	61.44	
393	m	2	1	0	302	312.19	104.06	416.25	712.70	NA	712.70		712.70	641.43	71.27	
393	m	3	1	0	302	473.66	157.89	631.55	1081.34	NA	1081.34		1081.34	973.21	108.13	
393	m	4	1	0	202	60.28	20.09	80.37	137.61	NA	137.61		137.61	123.85	13.76	
393	m	4	2	0	144	100.11	25.95	126.06	215.84	NA	215.84		215.84	194.26	21.58	
394	sq.m.	1	1	0	403	269.13	69.77	338.9	580.26	NA	580.26		580.26	464.21	116.05	
394	sq.m.	2	1	0	403	592.08	153.5	745.58	1276.58	NA	1276.58		1276.58	1021.27	255.32	
394	sq.m.	3	1	0	303	1076.5	279.09	1355.59	2321.04	606.88	606.88	1327.47	1474.96	1179.97	294.99	0.64
394	sq.m.	4	1	0	203	26.91	6.98	33.89	58.03	NA	58.03		58.03	46.42	11.61	
394	sq.m.	4	2	0	121	86.12	22.33	108.45	185.69	1156.37	1156.37	1321.48	1468.31	1174.65	293.66	7.91
395	sq.m.	1	1	0	402	269.13	89.71	358.84	614.41	NA	614.41		614.41	491.52	122.88	
395	sq.m.	2	1	0	204	26.91	6.98	33.89	58.03	NA	58.03		58.03	46.42	11.61	
395	sq.m.	3	1	0	204	26.91	6.98	33.89	58.03	NA	58.03		58.03	46.42	11.61	
395	sq.m.	3	2	0	121	107.65	27.91	135.56	232.11	1156.37	1156.37	1651.82	1835.35	1468.28	367.07	7.91
395	sq.m.	4	1	0	204	26.91	6.98	33.89	58.03	NA	58.03		58.03	46.42	11.61	
395	sq.m.	4	2	0	121	107.65	27.91	135.56	232.11	1156.37	1156.37	1651.82	1835.35	1468.28	367.07	7.91
396	sq.m.	1	1	0	405	269.13	69.77	338.9	580.26	NA	580.26		580.26	464.21	116.05	
396	sq.m.	2	1	0	221	34.66	8.99	43.65	74.74	NA	74.74		74.74	59.79	14.95	
396	sq.m.	3	1	0	221	34.66	8.99	43.65	74.74	NA	74.74		74.74	59.79	14.95	
396	sq.m.	3	2	0	121	75.36	19.54	94.9	162.49	1156.37	1156.37	1156.37	1284.86	1027.88	256.97	7.91
396	sq.m.	4	1	0	221	34.66	8.99	43.65	74.74	NA	74.74		74.74	59.79	14.95	
396	sq.m.	4	2	0	121	75.36	19.54	94.9	162.49	1156.37	1156.37	1156.37	1284.86	1027.88	256.97	7.91

Table 5.25. Complete list of updated unit costs for Pontis element actions (continued)

elemkey	metricunit	skey	akey	wholeflag	asubcat	varunitco	fixunitco	Cost2001	ExistCost2009	Cost2009	AdjCost2009	AdjElemCost2009	ElemCost2009	varunitco2009	fixunitco2009	Change
397	ea.	1	1	0	400	200	51.85	251.85	431.22	19.56	19.56	698.69	776.32	621.05	155.26	1.80
397	ea.	1	2	0	402	500	166.67	666.67	1141.47	NA	1141.47		1141.47	913.18	228.29	
397	ea.	2	1	0	400	200	51.85	251.85	431.22	19.56	19.56	698.69	776.32	621.05	155.26	1.80
397	ea.	2	2	0	423	500	129.63	629.63	1078.05	NA	1078.05		1078.05	862.44	215.61	
397	ea.	3	1	0	302	0	0	0	0.00	NA	0.00		0.00	0.00	0.00	
397	ea.	3	2	0	423	500	129.63	629.63	1078.05	NA	1078.05		1078.05	862.44	215.61	
397	ea.	4	1	0	302	0	0	0	0.00	NA	0.00		0.00	0.00	0.00	
397	ea.	4	2	0	423	500	129.63	629.63	1078.05	NA	1078.05		1078.05	862.44	215.61	
397	ea.	5	1	0	223	600	155.56	755.56	1293.67	NA	1293.67		1293.67	1034.94	258.73	
397	ea.	5	2	0	123	820	212.59	1032.59	1768.00	NA	1768.00		1768.00	1414.40	353.60	
398	ea.	1	1	0	405	100	25.93	125.93	215.62	NA	215.62		215.62	172.49	43.12	
398	ea.	2	1	0	400	200	51.85	251.85	431.22	19.56	19.56	698.69	776.32	621.05	155.26	1.80
398	ea.	2	2	0	423	500	129.63	629.63	1078.05	NA	1078.05		1078.05	862.44	215.61	
398	ea.	3	1	0	400	200	51.85	251.85	431.22	19.56	19.56	698.69	776.32	621.05	155.26	1.80
398	ea.	3	2	0	423	500	129.63	629.63	1078.05	NA	1078.05		1078.05	862.44	215.61	
398	ea.	4	1	0	202	492	164	656	1123.20	NA	1123.20		1123.20	898.56	224.64	
398	ea.	4	2	0	123	820	212.59	1032.59	1768.00	NA	1768.00		1768.00	1414.40	353.60	
399	m.	1	1	0	411	13.12	4.07	17.19	29.43	21.65	21.65	21.65	24.05	19.24	4.81	0.82
399	m.	2	1	0	211	262.48	81.46	343.94	588.89	281.27	281.27	304.08	337.86	270.29	67.57	0.57
399	m.	3	1	0	211	590.58	183.28	773.86	1325.00	281.27	281.27	684.17	760.19	608.15	152.04	0.57
399	m.	3	2	0	111	997.42	309.54	1306.96	2237.78	264.15	264.15	658.22	731.36	585.09	146.27	0.33
474	m.	1	1	0	402	82.03	27.34	109.37	187.26	NA	187.26		187.26	168.54	18.73	
474	m.	2	1	0	302	62.34	20.78	83.12	142.32	NA	142.32		142.32	128.09	14.23	
474	m.	3	1	0	302	95.15	31.72	126.87	217.23	NA	217.23		217.23	195.50	21.72	
474	m.	4	1	0	202	393.72	131.24	524.96	898.84	NA	898.84		898.84	808.95	89.88	
474	m.	4	2	0	144	200.14	51.89	252.03	431.53	NA	431.53		431.53	388.37	43.15	
475	m.	1	1	0	403	114.84	29.77	144.61	247.60	NA	247.60		247.60	222.84	24.76	
475	m.	2	1	0	403	131.24	34.03	165.27	282.98	NA	282.98		282.98	254.68	28.30	
475	m.	3	1	0	403	164.05	42.53	206.58	353.71	NA	353.71		353.71	318.34	35.37	
475	m.	4	1	0	203	1213.97	314.73	1528.7	2617.44	NA	2617.44		2617.44	2355.70	261.74	
475	m.	4	2	0	144	2001.41	518.88	2520.29	4315.24	NA	4315.24		4315.24	3883.72	431.52	
476	m.	1	1	0	404	82.03	21.27	103.3	176.87	NA	176.87		176.87	159.18	17.69	
476	m.	2	1	0	204	590.58	153.11	743.69	1273.35	NA	1273.35		1273.35	1146.01	127.33	
476	m.	3	1	0	204	590.58	153.11	743.69	1273.35	NA	1273.35		1273.35	1146.01	127.33	
476	m.	3	2	0	144	1000.71	259.44	1260.15	2157.63	NA	2157.63		2157.63	1941.87	215.76	
476	m.	4	1	0	204	590.58	153.11	743.69	1273.35	NA	1273.35		1273.35	1146.01	127.33	
476	m.	4	2	0	144	1000.71	259.44	1260.15	2157.63	NA	2157.63		2157.63	1941.87	215.76	
477	m.	1	1	0	405	82.03	21.27	103.3	176.87	NA	176.87		176.87	159.18	17.69	
477	m.	2	1	0	205	1312.4	340.25	1652.65	2829.67	NA	2829.67		2829.67	2546.70	282.97	
477	m.	3	1	0	205	1312.4	340.25	1652.65	2829.67	NA	2829.67		2829.67	2546.70	282.97	
477	m.	4	1	0	205	1312.4	340.25	1652.65	2829.67	NA	2829.67		2829.67	2546.70	282.97	
477	m.	4	2	0	144	2001.41	518.88	2520.29	4315.24	NA	4315.24		4315.24	3883.72	431.52	

Table 5.25. Complete list of updated unit costs for Pontis element actions (continued)

elemkey	metricunit	skey	akey	wholeflag	asubcat	varunitco	fixunitco	Cost2001	ExistCost2009	Cost2009	AdjCost2009	AdjElemCost2009	ElemCost2009	varunitco2009	fixunitco2009	Change
478	m.	1	1	0	406	82.03	21.27	103.3	176.87	NA	176.87		176.87	159.18	17.69	
478	m.	2	1	0	206	984.3	255.19	1239.49	2122.25	NA	2122.25		2122.25	1910.03	212.23	
478	m.	3	1	0	206	984.3	255.19	1239.49	2122.25	NA	2122.25		2122.25	1910.03	212.23	
478	m.	4	1	0	206	984.3	255.19	1239.49	2122.25	NA	2122.25		2122.25	1910.03	212.23	
478	m.	4	2	0	144	1200.85	311.33	1512.18	2589.15	NA	2589.15		2589.15	2330.24	258.92	
487	m.	1	1	0	402	82.03	27.34	109.37	187.26	NA	187.26		187.26	149.81	37.45	
487	m.	1	2	0	102	82.03	27.34	109.37	187.26	327.63	327.63	327.63	364.03	291.23	72.81	1.94
487	m.	2	1	0	400	32.81	8.51	41.32	70.75	19.56	19.56	114.63	127.37	101.89	25.47	1.80
487	m.	2	2	0	302	223.11	74.37	297.48	509.35	NA	509.35		509.35	407.48	101.87	
487	m.	3	1	0	302	223.11	74.37	297.48	509.35	NA	509.35		509.35	407.48	101.87	
487	m.	4	1	0	302	223.11	74.37	297.48	509.35	NA	509.35		509.35	407.48	101.87	
487	m.	4	2	0	102	170.61	56.87	227.48	389.49	327.63	327.63	681.44	757.16	605.73	151.43	1.94
487	m.	5	1	0	202	334.66	111.55	446.21	764.00	NA	764.00		764.00	611.20	152.80	
487	m.	5	2	0	151	689.01	178.63	867.64	1485.57	68922.50	68922.50	68922.50	76580.56	61264.44	15316.11	51.55
488	m.	1	1	0	400	32.81	8.51	41.32	70.75	19.56	19.56	114.63	127.37	101.89	25.47	1.80
488	m.	1	2	0	402	82.03	27.34	109.37	187.26	NA	187.26		187.26	149.81	37.45	
488	m.	2	1	0	400	32.81	8.51	41.32	70.75	19.56	19.56	114.63	127.37	101.89	25.47	1.80
488	m.	2	2	0	402	196.86	65.62	262.48	449.42	NA	449.42		449.42	359.53	89.88	
488	m.	3	1	0	302	223.11	74.37	297.48	509.35	NA	509.35		509.35	407.48	101.87	
488	m.	4	1	0	302	223.11	74.37	297.48	509.35	NA	509.35		509.35	407.48	101.87	
488	m.	4	2	0	102	170.61	56.87	227.48	389.49	327.63	327.63	681.44	757.16	605.73	151.43	1.94
488	m.	5	1	0	202	334.66	111.55	446.21	764.00	NA	764.00		764.00	611.20	152.80	
488	m.	5	2	0	151	689.01	178.63	867.64	1485.57	68922.50	68922.50	68922.50	76580.56	61264.44	15316.11	51.55
489	ea.	1	1	0	403	100	25.93	125.93	215.62	NA	215.62		215.62	172.49	43.12	
489	ea.	2	1	0	403	200	51.85	251.85	431.22	NA	431.22		431.22	344.97	86.24	
489	ea.	3	1	0	403	300	77.78	377.78	646.83	NA	646.83		646.83	517.47	129.37	
489	ea.	4	1	0	203	1000	259.26	1259.26	2156.10	NA	2156.10		2156.10	1724.88	431.22	
489	ea.	4	2	0	144	460	119.26	579.26	991.81	NA	991.81		991.81	793.45	198.36	
495	ea.	1	1	0	402	500	166.67	666.67	1141.47	NA	1141.47		1141.47	913.18	228.29	
495	ea.	2	1	0	302	500	166.67	666.67	1141.47	NA	1141.47		1141.47	913.18	228.29	
495	ea.	3	1	0	302	500	166.67	666.67	1141.47	NA	1141.47		1141.47	913.18	228.29	
495	ea.	4	1	0	202	6000	2000	8000	13697.60	NA	13697.60		13697.60	10958.08	2739.52	
495	ea.	4	2	0	151	10000	2592.59	12592.59	21561.03	68922.50	68922.50	1000314.40	1111460.44	889168.35	222292.09	51.55
496	ea.	1	1	0	400	200	51.85	251.85	431.22	19.56	19.56	698.69	776.32	621.05	155.26	1.80
496	ea.	1	2	0	402	500	166.67	666.67	1141.47	NA	1141.47		1141.47	913.18	228.29	
496	ea.	2	1	0	400	200	51.85	251.85	431.22	19.56	19.56	698.69	776.32	621.05	155.26	1.80
496	ea.	2	2	0	402	6000	2000	8000	13697.60	NA	13697.60		13697.60	10958.08	2739.52	
496	ea.	3	1	0	302	500	166.67	666.67	1141.47	NA	1141.47		1141.47	913.18	228.29	
496	ea.	4	1	0	302	500	166.67	666.67	1141.47	NA	1141.47		1141.47	913.18	228.29	
496	ea.	4	2	0	102	5000	1666.67	6666.67	11414.67	327.63	327.63	19970.83	22189.81	17751.85	4437.96	1.94
496	ea.	5	1	0	202	6000	2000	8000	13697.60	NA	13697.60		13697.60	10958.08	2739.52	
496	ea.	5	2	0	151	10000	2592.59	12592.59	21561.03	68922.50	68922.50	1000314.40	1111460.44	889168.35	222292.09	51.55

Table 5.25. Complete list of updated unit costs for Pontis element actions (continued)

elemkey	metricunit	skey	akey	wholeflag	asubcat	varunitco	fixunitco	Cost2001	ExistCost2009	Cost2009	AdjCost2009	AdjElemCost2009	ElemCost2009	varunitco2009	fixunitco2009	Change
497	ea.	1	1	0	400	200	51.85	251.85	431.22	19.56	19.56	698.69	776.32	621.05	155.26	1.80
497	ea.	1	2	0	402	500	166.67	666.67	1141.47	NA	1141.47		1141.47	913.18	228.29	
497	ea.	2	1	0	400	200	51.85	251.85	431.22	19.56	19.56	698.69	776.32	621.05	155.26	1.80
497	ea.	2	2	0	402	6000	2000	8000	13697.60	NA	13697.60		13697.60	10958.08	2739.52	
497	ea.	3	1	0	302	500	166.67	666.67	1141.47	NA	1141.47		1141.47	913.18	228.29	
497	ea.	4	1	0	302	500	166.67	666.67	1141.47	NA	1141.47		1141.47	913.18	228.29	
497	ea.	4	2	0	102	5000	1666.67	6666.67	11414.67	327.63	327.63	19970.83	22189.81	17751.85	4437.96	1.94
497	ea.	5	1	0	202	6000	2000	8000	13697.60	NA	13697.60		13697.60	10958.08	2739.52	
497	ea.	5	2	0	151	10000	2592.59	12592.59	21561.03	68922.50	68922.50	1000314.40	1111460.44	889168.35	222292.09	51.55
498	ea.	1	1	0	402	500	166.67	666.67	1141.47	NA	1141.47		1141.47	913.18	228.29	
498	ea.	2	1	0	202	6000	2000	8000	13697.60	NA	13697.60		13697.60	10958.08	2739.52	
498	ea.	3	1	0	202	6000	2000	8000	13697.60	NA	13697.60		13697.60	10958.08	2739.52	
498	ea.	4	1	0	202	6000	2000	8000	13697.60	NA	13697.60		13697.60	10958.08	2739.52	
498	ea.	4	2	0	151	10000	2592.59	12592.59	21561.03	68922.50	68922.50	1000314.40	1111460.44	889168.35	222292.09	51.55
499	ea.	1	1	0	403	100	25.93	125.93	215.62	NA	215.62		215.62	172.49	43.12	
499	ea.	2	1	0	403	200	51.85	251.85	431.22	NA	431.22		431.22	344.97	86.24	
499	ea.	3	1	0	403	300	77.78	377.78	646.83	NA	646.83		646.83	517.47	129.37	
499	ea.	4	1	0	203	1000	259.26	1259.26	2156.10	NA	2156.10		2156.10	1724.88	431.22	
499	ea.	4	2	0	151	2000	518.52	2518.52	4312.21	68922.50	68922.50	200063.04	222292.26	177833.81	44458.45	51.55
540	ea.	1	1	0	431	2810	728.52	3538.52	6058.65	NA	6058.65		6058.65	4846.92	1211.73	
540	ea.	2	1	0	331	5620	1457.04	7077.04	12117.31	NA	12117.31		12117.31	9693.85	2423.46	
540	ea.	3	1	0	231	11300	2929.63	14229.63	24363.97	NA	24363.97		24363.97	19491.18	4872.79	
540	ea.	3	2	0	131	28500	7388.89	35888.89	61448.96	NA	61448.96		61448.96	49159.17	12289.79	
540	ea.	4	1	0	131	28500	7388.89	35888.89	61448.96	NA	61448.96		61448.96	49159.17	12289.79	
541	ea.	1	1	0	431	4060	1052.59	5112.59	8753.78	NA	8753.78		8753.78	7003.02	1750.76	
541	ea.	2	1	0	331	8120	2105.19	10225.19	17507.57	NA	17507.57		17507.57	14006.06	3501.51	
541	ea.	3	1	0	231	16300	4225.93	20525.93	35144.50	NA	35144.50		35144.50	28115.60	7028.90	
541	ea.	3	2	0	131	39000	10111.11	49111.11	84088.04	NA	84088.04		84088.04	67270.43	16817.61	
541	ea.	4	1	0	131	39000	10111.11	49111.11	84088.04	NA	84088.04		84088.04	67270.43	16817.61	
542	ea.	1	1	0	431	210	54.44	264.44	452.77	NA	452.77		452.77	362.22	90.55	
542	ea.	2	1	0	331	420	108.89	528.89	905.57	NA	905.57		905.57	724.45	181.11	
542	ea.	3	1	0	231	900	233.33	1133.33	1940.49	NA	1940.49		1940.49	1552.39	388.10	
542	ea.	3	2	0	131	2900	751.85	3651.85	6252.70	NA	6252.70		6252.70	5002.16	1250.54	
542	ea.	4	1	0	131	2900	751.85	3651.85	6252.70	NA	6252.70		6252.70	5002.16	1250.54	
543	ea.	1	1	0	431	170	44.07	214.07	366.53	NA	366.53		366.53	293.22	73.31	
543	ea.	2	1	0	331	330	85.56	415.56	711.52	NA	711.52		711.52	569.22	142.30	
543	ea.	3	1	0	231	700	181.48	881.48	1509.27	NA	1509.27		1509.27	1207.42	301.85	
543	ea.	3	2	0	131	750	194.44	944.44	1617.07	NA	1617.07		1617.07	1293.66	323.41	
543	ea.	4	1	0	131	750	194.44	944.44	1617.07	NA	1617.07		1617.07	1293.66	323.41	
544	ea.	1	1	0	431	225	58.33	283.33	485.12	NA	485.12		485.12	388.09	97.02	
544	ea.	2	1	0	331	450	116.67	566.67	970.25	NA	970.25		970.25	776.20	194.05	
544	ea.	3	1	0	231	900	233.33	1133.33	1940.49	NA	1940.49		1940.49	1552.39	388.10	
544	ea.	3	2	0	131	980	254.07	1234.07	2112.97	NA	2112.97		2112.97	1690.38	422.59	
544	ea.	4	1	0	231	2700	700	3400	5821.48	NA	5821.48		5821.48	4657.18	1164.30	
544	ea.	4	2	0	131	980	254.07	1234.07	2112.97	NA	2112.97		2112.97	1690.38	422.59	

Table 5.25. Complete list of updated unit costs for Pontis element actions (continued)

elemkey	metricunit	skey	akey	wholeflag	asubcat	varunitco	fixunitco	Cost2001	ExistCost2009	Cost2009	AdjCost2009	AdjElemCost2009	ElemCost2009	varunitco2009	fixunitco2009	Change
545	ea.	1	1	0	431	460	119.26	579.26	991.81	NA	991.81		991.81	793.45	198.36	
545	ea.	2	1	0	431	460	119.26	579.26	991.81	NA	991.81		991.81	793.45	198.36	
545	ea.	3	1	0	231	1900	492.59	2392.59	4096.59	NA	4096.59		4096.59	3277.27	819.32	
545	ea.	3	2	0	131	4500	1166.67	5666.67	9702.47	NA	9702.47		9702.47	7761.98	1940.49	
545	ea.	4	1	0	131	4500	1166.67	5666.67	9702.47	NA	9702.47		9702.47	7761.98	1940.49	
546	ea.	1	1	0	431	710	184.07	894.07	1530.83	NA	1530.83		1530.83	1224.66	306.17	
546	ea.	2	1	0	431	710	184.07	894.07	1530.83	NA	1530.83		1530.83	1224.66	306.17	
546	ea.	3	1	0	231	2900	751.85	3651.85	6252.70	NA	6252.70		6252.70	5002.16	1250.54	
546	ea.	3	2	0	131	6700	1737.04	8437.04	14445.90	NA	14445.90		14445.90	11556.72	2889.18	
546	ea.	4	1	0	131	6700	1737.04	8437.04	14445.90	NA	14445.90		14445.90	11556.72	2889.18	
547	ea.	1	1	0	431	1370	355.19	1725.19	2953.87	NA	2953.87		2953.87	2363.10	590.77	
547	ea.	2	1	0	431	1370	355.19	1725.19	2953.87	NA	2953.87		2953.87	2363.10	590.77	
547	ea.	3	1	0	231	5500	1425.93	6925.93	11858.58	NA	11858.58		11858.58	9486.86	2371.72	
547	ea.	3	2	0	131	41500	10759.26	52259.26	89478.30	NA	89478.30		89478.30	71582.64	17895.66	
547	ea.	4	1	0	131	41500	10759.26	52259.26	89478.30	NA	89478.30		89478.30	71582.64	17895.66	
548	ea.	1	1	0	431	330	85.56	415.56	711.52	NA	711.52		711.52	569.22	142.30	
548	ea.	2	1	0	431	330	85.56	415.56	711.52	NA	711.52		711.52	569.22	142.30	
548	ea.	3	1	0	231	1400	362.96	1762.96	3018.54	NA	3018.54		3018.54	2414.83	603.71	
548	ea.	3	2	0	131	3200	829.63	4029.63	6899.53	NA	6899.53		6899.53	5519.63	1379.91	
549	ea.	1	1	0	431	750	194.44	944.44	1617.07	NA	1617.07		1617.07	1293.66	323.41	
549	ea.	2	1	0	431	750	194.44	944.44	1617.07	NA	1617.07		1617.07	1293.66	323.41	
549	ea.	3	1	0	231	3000	777.78	3777.78	6468.31	NA	6468.31		6468.31	5174.65	1293.66	
549	ea.	3	2	0	131	9000	2333.33	11333.33	19404.93	NA	19404.93		19404.93	15523.94	3880.99	
549	ea.	4	1	0	131	9000	2333.33	11333.33	19404.93	NA	19404.93		19404.93	15523.94	3880.99	
550	ea.	1	1	0	400	200	51.85	251.85	431.22	19.56	19.56	698.69	776.32	621.05	155.26	1.80
550	ea.	1	2	0	431	1400	362.96	1762.96	3018.54	NA	3018.54		3018.54	2414.83	603.71	
550	ea.	2	1	0	400	200	51.85	251.85	431.22	19.56	19.56	698.69	776.32	621.05	155.26	1.80
550	ea.	2	2	0	402	5000	1666.67	6666.67	11414.67	NA	11414.67		11414.67	9131.74	2282.93	
550	ea.	3	1	0	302	500	166.67	666.67	1141.47	NA	1141.47		1141.47	913.18	228.29	
550	ea.	4	1	0	302	500	166.67	666.67	1141.47	NA	1141.47		1141.47	913.18	228.29	
550	ea.	4	2	0	102	5000	1666.67	6666.67	11414.67	327.63	327.63	19970.83	22189.81	17751.85	4437.96	1.94
550	ea.	5	1	0	231	5600	1451.85	7051.85	12074.18	NA	12074.18		12074.18	9659.34	2414.84	
550	ea.	5	2	0	131	35000	9074.07	44074.07	75463.62	NA	75463.62		75463.62	60370.90	15092.72	
560	ea.	1	1	0	431	1370	355.19	1725.19	2953.87	NA	2953.87		2953.87	2363.10	590.77	
560	ea.	2	1	0	431	1370	355.19	1725.19	2953.87	NA	2953.87		2953.87	2363.10	590.77	
560	ea.	3	1	0	231	5500	1425.93	6925.93	11858.58	NA	11858.58		11858.58	9486.86	2371.72	
560	ea.	3	2	0	131	2800	725.93	3525.93	6037.10	NA	6037.10		6037.10	4829.68	1207.42	
560	ea.	4	1	0	131	2800	725.93	3525.93	6037.10	NA	6037.10		6037.10	4829.68	1207.42	
561	ea.	1	1	0	431	750	194.44	944.44	1617.07	NA	1617.07		1617.07	1293.66	323.41	
561	ea.	2	1	0	302	500	166.67	666.67	1141.47	NA	1141.47		1141.47	913.18	228.29	
561	ea.	2	2	0	331	1500	388.89	1888.89	3234.16	NA	3234.16		3234.16	2587.33	646.83	
561	ea.	3	1	0	231	3000	777.78	3777.78	6468.31	NA	6468.31		6468.31	5174.65	1293.66	
561	ea.	3	2	0	131	7000	1814.81	8814.81	15092.72	NA	15092.72		15092.72	12074.17	3018.54	

Table 5.25. Complete list of updated unit costs for Pontis element actions (continued)

elemkey	metricunit	skey	akey	wholeflag	asubcat	varunitco	fixunitco	Cost2001	ExistCost2009	Cost2009	AdjCost2009	AdjElemCost2009	ElemCost2009	varunitco2009	fixunitco2009	Change
562	ea.	1	1	0	400	200	51.85	251.85	431.22	19.56	19.56	698.69	776.32	621.05	155.26	1.80
562	ea.	1	2	0	431	400	103.7	503.7	862.44	NA	862.44		862.44	689.95	172.49	
562	ea.	2	1	0	400	200	51.85	251.85	431.22	19.56	19.56	698.69	776.32	621.05	155.26	1.80
562	ea.	2	2	0	402	5000	1666.67	6666.67	11414.67	NA	11414.67		11414.67	9131.74	2282.93	
562	ea.	3	1	0	302	500	166.67	666.67	1141.47	NA	1141.47		1141.47	913.18	228.29	
562	ea.	4	1	0	302	500	166.67	666.67	1141.47	NA	1141.47		1141.47	913.18	228.29	
562	ea.	4	2	0	102	5000	1666.67	6666.67	11414.67	327.63	327.63	19970.83	22189.81	17751.85	4437.96	1.94
562	ea.	5	1	0	231	1600	414.81	2014.81	3449.76	NA	3449.76		3449.76	2759.81	689.95	
562	ea.	5	2	0	131	3000	777.78	3777.78	6468.31	NA	6468.31		6468.31	5174.65	1293.66	
563	ea.	1	1	0	400	200	51.85	251.85	431.22	19.56	19.56	698.69	776.32	621.05	155.26	1.80
563	ea.	1	2	0	431	450	116.67	566.67	970.25	NA	970.25		970.25	776.20	194.05	
563	ea.	2	1	0	400	200	51.85	251.85	431.22	19.56	19.56	698.69	776.32	621.05	155.26	1.80
563	ea.	2	2	0	402	1000	333.33	1333.33	2282.93	NA	2282.93		2282.93	1826.34	456.59	
563	ea.	3	1	0	302	250	83.33	333.33	570.73	NA	570.73		570.73	456.58	114.15	
563	ea.	4	1	0	302	250	83.33	333.33	570.73	NA	570.73		570.73	456.58	114.15	
563	ea.	4	2	0	102	2500	833.33	3333.33	5707.33	327.63	327.63	9985.40	11094.89	8875.91	2218.98	1.94
563	ea.	5	1	0	231	1800	466.67	2266.67	3880.99	NA	3880.99		3880.99	3104.79	776.20	
563	ea.	5	2	0	131	2900	751.85	3651.85	6252.70	NA	6252.70		6252.70	5002.16	1250.54	
564	ea.	1	1	0	431	0	0	0	0.00	NA	0.00		0.00	0.00	0.00	
564	ea.	2	1	0	403	0	0	0	0.00	NA	0.00		0.00	0.00	0.00	
564	ea.	3	1	0	403	0	0	0	0.00	NA	0.00		0.00	0.00	0.00	
564	ea.	4	1	0	203	4500	1166.67	5666.67	9702.47	NA	9702.47		9702.47	7761.98	1940.49	
564	ea.	4	2	0	131	9000	2333.33	11333.33	19404.93	NA	19404.93		19404.93	15523.94	3880.99	
565	ea.	1	1	0	431	325	84.26	409.26	700.73	NA	700.73		700.73	560.59	140.15	
565	ea.	2	1	0	331	650	168.52	818.52	1401.47	NA	1401.47		1401.47	1121.18	280.29	
565	ea.	3	1	0	231	1300	337.04	1637.04	2802.94	NA	2802.94		2802.94	2242.35	560.59	
565	ea.	3	2	0	131	9000	2333.33	11333.33	19404.93	NA	19404.93		19404.93	15523.94	3880.99	
565	ea.	4	1	0	131	9000	2333.33	11333.33	19404.93	NA	19404.93		19404.93	15523.94	3880.99	
570	ea.	1	1	0	431	80	20.74	100.74	172.49	NA	172.49		172.49	137.99	34.50	
570	ea.	2	1	0	331	150	38.89	188.89	323.42	NA	323.42		323.42	258.73	64.68	
570	ea.	3	1	0	231	300	77.78	377.78	646.83	NA	646.83		646.83	517.47	129.37	
570	ea.	3	2	0	131	1500	388.89	1888.89	3234.16	NA	3234.16		3234.16	2587.33	646.83	
571	ea.	1	1	0	431	290	75.19	365.19	625.28	NA	625.28		625.28	500.22	125.06	
571	ea.	2	1	0	231	1150	298.15	1448.15	2479.52	NA	2479.52		2479.52	1983.62	495.90	
571	ea.	3	1	0	231	2300	596.3	2896.3	4959.04	NA	4959.04		4959.04	3967.24	991.81	
571	ea.	3	2	0	131	10800	2800	13600	23285.92	NA	23285.92		23285.92	18628.74	4657.18	
572	ea.	1	1	0	431	100	25.93	125.93	215.62	NA	215.62		215.62	172.49	43.12	
572	ea.	2	1	1	231	400	103.7	503.7	862.44	NA	862.44		862.44	689.95	172.49	
572	ea.	3	1	1	231	1650	427.78	2077.78	3557.57	NA	3557.57		3557.57	2846.06	711.51	
572	ea.	3	2	1	131	600	155.56	755.56	1293.67	NA	1293.67		1293.67	1034.94	258.73	

Table 5.25. Complete list of updated unit costs for Pontis element actions (continued)

elemkey	metricunit	skey	akey	wholeflag	asubcat	varunitco	fixunitco	Cost2001	ExistCost2009	Cost2009	AdjCost2009	AdjElemCost2009	ElemCost2009	varunitco2009	fixunitco2009	Change
573	ea.	1	1	0	431	6330	1641.11	7971.11	13648.13	NA	13648.13		13648.13	10918.51	2729.63	
573	ea.	2	1	0	431	6330	1641.11	7971.11	13648.13	NA	13648.13		13648.13	10918.51	2729.63	
573	ea.	3	1	0	231	25300	6559.26	31859.26	54549.42	NA	54549.42		54549.42	43639.54	10909.88	
573	ea.	3	2	0	131	40400	10474.07	50874.07	87106.58	NA	87106.58		87106.58	69685.27	17421.32	
574	ea.	1	1	0	431	5080	1317.04	6397.04	10953.01	NA	10953.01		10953.01	8762.41	2190.60	
574	ea.	2	1	0	431	5080	1317.04	6397.04	10953.01	NA	10953.01		10953.01	8762.41	2190.60	
574	ea.	3	1	0	231	20300	5262.96	25562.96	43768.90	NA	43768.90		43768.90	35015.12	8753.78	
574	ea.	3	2	0	131	30900	8011.11	38911.11	66623.60	NA	66623.60		66623.60	53298.88	13324.72	
580	ea.	1	1	0	431	490	127.04	617.04	1056.50	NA	1056.50		1056.50	845.20	211.30	
580	ea.	2	1	0	431	490	127.04	617.04	1056.50	NA	1056.50		1056.50	845.20	211.30	
580	ea.	3	1	0	231	1930	500.37	2430.37	4161.28	NA	4161.28		4161.28	3329.02	832.26	
580	ea.	3	2	0	131	1000	259.26	1259.26	2156.10	NA	2156.10		2156.10	1724.88	431.22	
581	ea.	1	1	0	431	2170	562.59	2732.59	4678.74	NA	4678.74		4678.74	3742.99	935.75	
581	ea.	2	1	0	231	8700	2255.56	10955.56	18758.11	NA	18758.11		18758.11	15006.49	3751.62	
581	ea.	2	2	0	131	28000	7259.26	35259.26	60370.90	NA	60370.90		60370.90	48296.72	12074.18	
581	ea.	3	1	0	231	21200	5496.3	26696.3	45709.40	NA	45709.40		45709.40	36567.52	9141.88	
581	ea.	3	2	0	131	28000	7259.26	35259.26	60370.90	NA	60370.90		60370.90	48296.72	12074.18	
582	ea.	1	1	0	431	6250	1620.37	7870.37	13475.65	NA	13475.65		13475.65	10780.52	2695.13	
582	ea.	2	1	0	431	6250	1620.37	7870.37	13475.65	NA	13475.65		13475.65	10780.52	2695.13	
582	ea.	2	2	0	231	25000	6481.48	31481.48	53902.59	NA	53902.59		53902.59	43122.07	10780.52	
582	ea.	3	1	0	231	25000	6481.48	31481.48	53902.59	NA	53902.59		53902.59	43122.07	10780.52	
582	ea.	3	2	0	131	50000	12962.96	62962.96	107805.18	NA	107805.18		107805.18	86244.14	21561.04	
583	ea.	1	1	0	431	6250	1620.37	7870.37	13475.65	NA	13475.65		13475.65	10780.52	2695.13	
583	ea.	2	1	0	431	6250	1620.37	7870.37	13475.65	NA	13475.65		13475.65	10780.52	2695.13	
583	ea.	2	2	0	231	25000	6481.48	31481.48	53902.59	NA	53902.59		53902.59	43122.07	10780.52	
583	ea.	3	1	0	231	25000	6481.48	31481.48	53902.59	NA	53902.59		53902.59	43122.07	10780.52	
583	ea.	3	2	0	131	50000	12962.96	62962.96	107805.18	NA	107805.18		107805.18	86244.14	21561.04	
590	ea.	1	1	0	431	130	33.7	163.7	280.29	NA	280.29		280.29	224.23	56.06	
590	ea.	2	1	0	431	130	33.7	163.7	280.29	NA	280.29		280.29	224.23	56.06	
590	ea.	2	2	0	231	500	129.63	629.63	1078.05	NA	1078.05		1078.05	862.44	215.61	
590	ea.	3	1	0	231	750	194.44	944.44	1617.07	NA	1617.07		1617.07	1293.66	323.41	
590	ea.	3	2	0	131	800	207.41	1007.41	1724.89	NA	1724.89		1724.89	1379.91	344.98	
591	ea.	1	1	0	431	330	85.56	415.56	711.52	NA	711.52		711.52	569.22	142.30	
591	ea.	2	1	0	431	330	85.56	415.56	711.52	NA	711.52		711.52	569.22	142.30	
591	ea.	2	2	0	231	1300	337.04	1637.04	2802.94	NA	2802.94		2802.94	2242.35	560.59	
591	ea.	3	1	0	231	4100	1062.96	5162.96	8840.02	NA	8840.02		8840.02	7072.02	1768.00	
591	ea.	3	2	0	131	7000	1814.81	8814.81	15092.72	NA	15092.72		15092.72	12074.17	3018.54	
592	ea.	1	1	0	431	290	75.19	365.19	625.28	NA	625.28		625.28	500.22	125.06	
592	ea.	2	1	0	431	290	75.19	365.19	625.28	NA	625.28		625.28	500.22	125.06	
592	ea.	2	2	0	231	1200	311.11	1511.11	2587.32	NA	2587.32		2587.32	2069.86	517.46	
592	ea.	3	1	0	231	3300	855.56	4155.56	7115.15	NA	7115.15		7115.15	5692.12	1423.03	
592	ea.	3	2	0	131	5200	1348.15	6548.15	11211.74	NA	11211.74		11211.74	8969.39	2242.35	

6. Models of User Cost When no Detour Exists

This section presents results of the modeling effort on estimating user costs at bridge sites where no detour is considered. These involved research efforts to develop a model for quantifying the economic effect on road users if mobility is restricted by bridge deficiencies, and no detour route exists.

6.1 Introduction

Users cost models are used in bridge management systems (BMS) to quantify, in economic terms, the existing deficiencies, or the potential safety and mobility benefits of functional improvements to bridges. Road users typically incur some costs in using an existing transportation facility, but the term "user cost" in BMS is really relative, i.e., the costs incurred by road users due to deficiencies associated with the particular facility, relative to when the facility is in an ideal state or a desired level of service. User costs can be broken down into three primary components: travel time costs; vehicle operating costs; and accident risk costs. Due to delays in using bridges, users incur travel time costs. Vehicle operating costs may also increase. Safety may also be potentially compromised on bridges with certain deficient attributes, leading to possible accident costs.

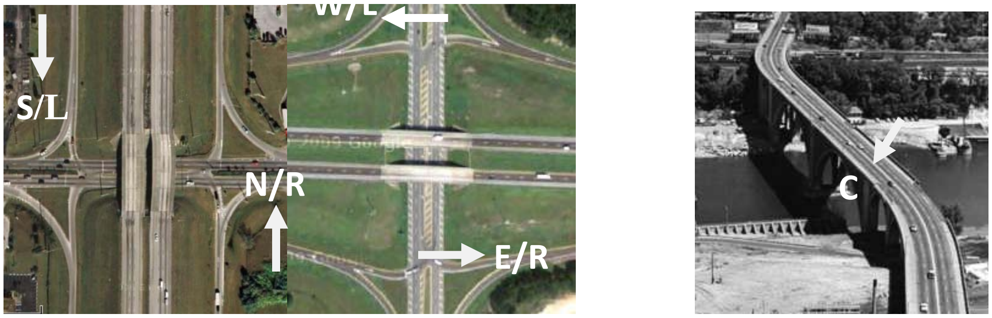
6.1.1 Data preparation

According to the Florida Department of Transportation's (FDOT)'s 2008 Pontis Database (*Bridge*, *Roadway*, and *Inspvent* Tables), there are a total of 19,213 structures in Florida, of which 11,802 are bridges carrying roadway routes. Using only bridge data with roadway routes, a cleanup and refinement of the data were done using "proper" roadway attributes (roadway width, number of lanes, roadway speed, traffic volume, and bridge length) reducing the inventory list to 9,448 bridges. With the research focus being on state-maintained and toll bridges, i.e., with NBI ownership codes 1, 31, and 33, these 9,448 bridges were further reduced to a final list of 5,435 bridges.

The Pontis working data set was then matched to pertinent crash data in the FDOT Crash Analysis and Reporting (CAR) database. Since crash data are available for only 2003 to 2007, these five years' data were chosen for analysis. The CAR's data is primarily based on crashes reported by police officers. It contains various items of data to identify each accident, including the date, time and location of crash; driver, vehicle, and weather information; injuries; and other circumstances. However, very little data are provided about bridges. It was necessary to introduce the third database, the FDOT Geographic Information System (GIS) bridge database, which contains the same bridges as the Pontis database, using the same Bridge IDs, and also the same linear referencing system (County, Section, Subsection, and Mile-Post) as the CAR's database. Consequently, this makes it relatively straightforward to develop a process to merge the three data sets. Using the GIS data it was possible to precisely locate the beginning and end of each bridge along the roadway. Following the recommendation made by (Brinkman and Mak, 1986), and also followed by (Johnston et al. 1994), all accidents from the HSMV database that were located within 500 feet of the beginning or end of a bridge were attributed to that bridge.

The initial matching process showed that many of the crashes were assigned to multiple bridges. Most of them involved two or more parallel bridges, and the remaining cases involved bridges in series that are less than 1000 feet apart. Thompson (1999) suggested that since the functional characteristics of the nearby bridges tend to be identical, it could be assumed that each bridge was equally likely to be associated with the accident. Also, the CAR database provides information on the heading (geographical) direction of the at-fault vehicle; this makes it easier to correctly identify the specific bridge structure. According to the FDOT's linear referencing system, the roadway mile-post (number) is ascending from

South to North, as well as from West to East, thus we could make use of this attribute to determine the side of the roadway on which the crash-affected bridge structure is located. As shown in Figure 6.1.(a) for a divided roadway, when the direction of the at-fault vehicle is west (W) or south (S), the crash would have occurred on the left (L) side of the roadway centerline, which means the crash should be assigned to the left side structure, otherwise it should have happened on the right (R) side structure. If the bridge structure does not have a parallel bridge (Figure 6.1.(b)), the heading direction of the at-fault vehicle is not relevant.



(a) Two bridge structures (b) Single bridge (C)

Figure 6.1. Bridge structure on the side of roadway

Shown in the following figures are monthly, daily, and hourly variations of the occurrence of crashes on bridges. From Figures 6.2 to 6.4 shown for crashes on bridges in Florida for the year 2003, the month March seems have relatively more crashes than other months, and the day Friday appears to have higher crash risk than other days. But overall, both the monthly and weekly histograms give the impression of being a uniform distribution which means there is little monthly or daily influence that would affect the development of the user cost model. From the hourly histogram (Figure 6.4), it appears that rush hour in the afternoon (4-6 PM) has the highest accident risks of occurrence on the bridge, with the morning peak hour (6-8 AM) also being significant.

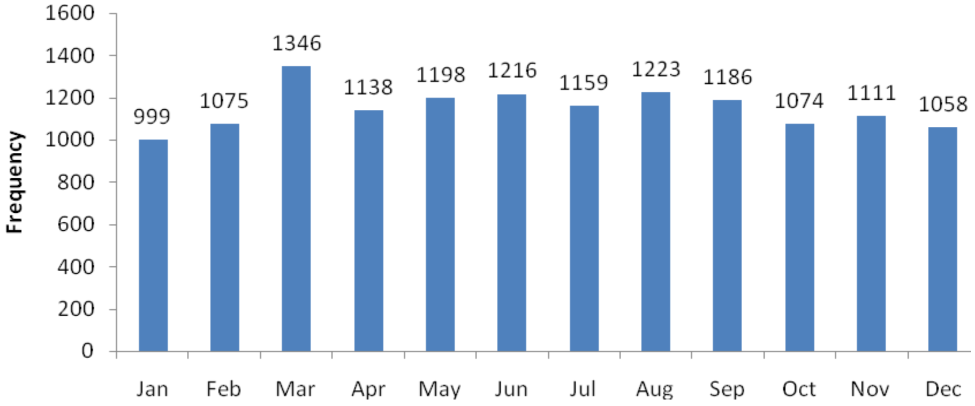


Figure 6.2. Crash monthly histogram in 2003

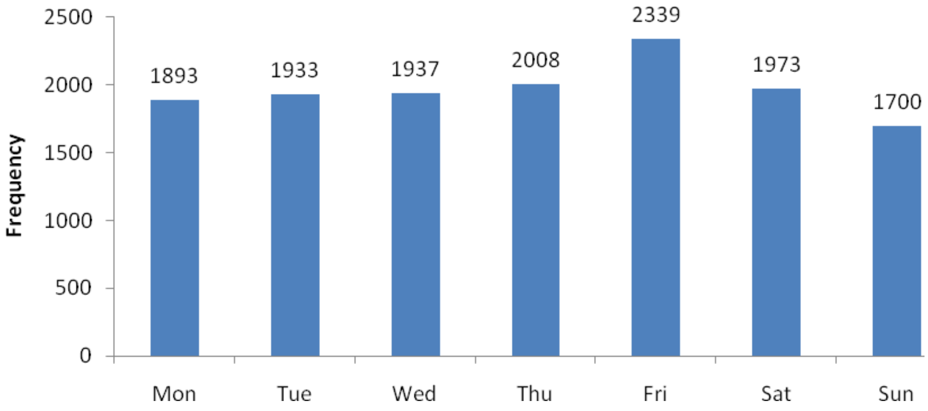


Figure 6.3. Crash weekly histogram in 2003

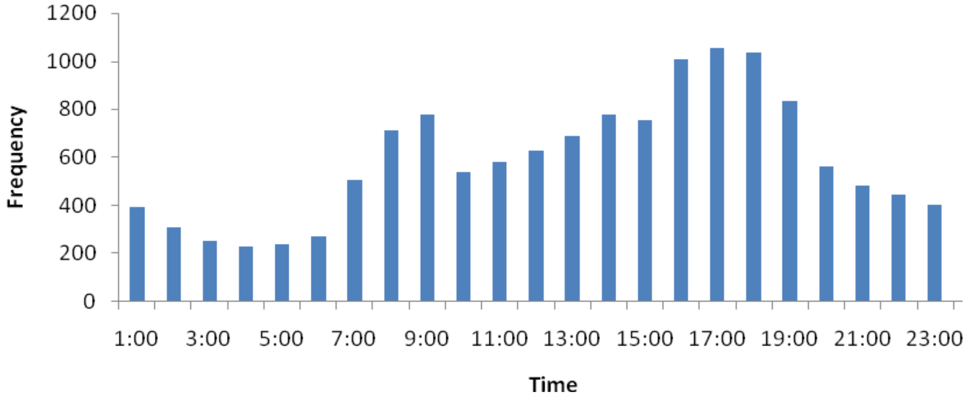


Figure 6.4. Crash hourly histogram in 2003

6.2 Existing Pontis User Cost Model

A previous pertinent study on user cost on Florida bridges (Thompson 1999) suggested that bridge functional deficiencies such as width, clearance, and deck surface condition, are the bridge characteristics having the greatest statistical association with increased user costs. Benefits of functional improvements in Pontis are also assessed in terms of user cost savings (Golabi et.al. 1992 and Blundell 1997). When there is a deficient approach alignment or roadway width on a bridge, road users are theoretically subject to higher accident risk. To evaluate a functional improvement or replacement, which corrects the deficiency, the user cost model predicts a reduction in accident risk, which then is multiplied by an accident cost to yield user cost savings. Also, when a bridge has substandard vertical clearance or load capacity, certain trucks are unable to pass on or under the bridges and must detour, thus incurring higher driver labor costs and vehicle operating costs. The user cost model estimates the volume of detoured traffic and the resulting user cost, which would be avoided if the deficiency were corrected. The total user benefit B_r, of the functional improvement in a project can be computed as follows:

$$B_r = \frac{W_C}{100} \times V_{ry}(BW_r + BR_r + BS_r) \tag{6.1}$$

where: W_C = the weight given to user cost benefits, in percent (Pontis cost matrix)
V_{ry} = forecast average daily traffic volume for the program year being analyzed

BW_r = annual benefit of widening per unit average daily traffic
BR_r = annual benefit of raising per unit average daily traffic
BS_r = annual benefit of strengthening per unit average daily traffic

Estimates of the user benefits associated with raising and strengthening are primarily based on detour length caused by bridge functional deficiencies. However, in this study, the emphasis is on estimating the excess user costs or benefits when a detour route is either not available or not being considered.

6.3. Travel time costs

Considering that users on the roadway or bridges need to optimize their valuable time, it is important to be able to estimate travel times on the bridge, especially, in evaluating the effects of the bridge and its related attributes. Travel time is one of the major issues considered in the evaluation of alternative transportation systems, with the cost of travel time calculated as the product of the amount of travel time and the value of travel time. But first it is important to know which factors affect travel time costs, as shown in Table 6.1.

Table 6.1. Factors affecting value and amount of travel time (Source: Sinha and Labi 2007)

Factors affecting amount of travel time	Factors affecting value of travel time
How long does it take to travel?	*What is the dollar value of 1hour of travel?*
Trip length	Mode and vehicle of travel
Vehicle speed	Trip purpose and urgency
Vehicle occupancy	Time of day, day of week, season of year
Other factors	Trip location
Weather	Traveler's socioeconomic background
Security concerns	Relationship between amount of time used for trip and time used for waiting

6.3.1 The amount of travel time

In certain cases, the approach roadway speed will be reduced to a lower speed on the bridge due to the deficiencies of a narrow bridge, including narrowed lane width, reduced number of lanes, and narrowed shoulder clearance. The data for approach roadway speed is available in the Pontis bridge inventory database. According to Sinha and Labi (2007), to estimate the approach roadway speed changes, an equation based on the bridge narrowness is shown as follows, with the adjustment factors shown in Tables 6.2 to 6.4.

$$FFS_1 = BFFS - f_{lw} - f_{lc} - f_n \tag{6.2}$$

Where: FFS_1 = estimated bridge speed (mph)
$BFFS$ = based free flow speed on the approach roadway
f_{lw} = adjustment factor for lane width (mph)
f_{lc} = adjustment factor for lateral clearance (mph)
f_n = adjustment factor for number of lanes (mph)

Table 6.2. Adjustment for lane width

lane width (ft)	f_{lw} (mph)
12	0
11	1.9
10	6.6

Table 6.3. Adjustment for shoulder lateral clearance

shoulder lateral clearance (ft)	f_{lc} (mph) based on number of lanes		
	2	3	4
6	0	0	0
5	0.6	0.4	0.2
4	1.2	0.8	0.4
3	1.8	1.2	0.6
2	2.4	1.6	0.8
1	3	2	1
0	3.6	2.4	1.2

Table 6.4. Adjustment for number of lanes

Number of lanes	f_n (mph)
5	0
4	1.5
3	3
2	4.5

If the bridge deck surface is rough, a speed reduction may also occur, due to the driver's discomfort and vehicle maintenance requirements, resulting in travel time delay and costs. Paterson and Watanatada (1985) are known for the initial work on models for estimating vehicle speeds based on roadway surface roughness. Archondo-Callao (1999) also reported the variation between maximum speeds and roadway roughness, from a HDM-III model based on the Brazil-UNDP Study. Both studies were World Bank-sponsored research on unpaved roadways. Table 6.5 shows a relationship between a measure of roadway surface roughness (the International Roughness Index (IRI)) and the roadway speed, while the trend is shown in Figure 6.5. There should be some caution in the direct application of these models to modern paved roadways but they are applied here for illustration purposes only, pending the availability of an appropriate model.

Table 6.5. Variation in roadway speeds relative to surface roughness (Archondo-Callao 1999)

Maximum Speeds (km/h) for Vehicle Types						
Cars	Utilities	Buses	Light Trucks	Medium/ Heavy Trucks	Articulated Trucks	Roughness (IRI) (m/km)
136	125	111	102	93	68	6
102	94	84	76	70	51	8
82	75	67	61	56	41	10
68	63	56	51	46	34	12
58	54	48	44	40	29	14
51	47	42	38	35	26	16
45	42	37	34	31	23	18
4						

Figure 6.5. Variation in roadway speeds relative to surface roughness (Source: Archondo-Callao 1999)

The fitted equation relating the speed to roughness shown below, is also indicated in Figure 6.5 for Medium/Heavy trucks; the applicable unit conversion rates are 1 mph = 0.621 km/h, for the speed and 1 in/mi = 0.015783 m/km for the IRI.

$$FFS_2 = -0.030*IRI^3 + 1.534*IRI^2 - 27.853*IRI + 210.929 \quad (6.3)$$

where FFS_2 = predicted vehicle speed (km/h), assumed as the speed on the bridge
IRI = International Roughness Index for the roadway surface (m/km).

Based on these two methods of estimating the speeds on the bridge as shown in equations 6.2 and 6.3 above, an appropriate bridge speed could be conservatively determined as the minimum of the two, i.e.,

$$\mathbf{FFS} = \min\begin{pmatrix}\mathbf{FFS_1}\\ \mathbf{FFS_2}\end{pmatrix} \quad (6.4)$$

A Microsoft Excel spreadsheet template was developed to compute travel time costs based on the two types of bridge speed limits, i.e. FFS_1 and FFS_2. But since information on the bridge surface roughness (IRI) is not available for Florida bridges at the current time, only FFS_1 was really considered. Based on the results calculated for the bridges from the Florida inventory, the distribution is shown as a histogram in Figure 6.6 for the approach (freeway) roadway speed and speed on the bridges. It can be seen that generally, travel speeds on the bridges are lower than those of the approach roadways, which introduces extra travel time on bridges.

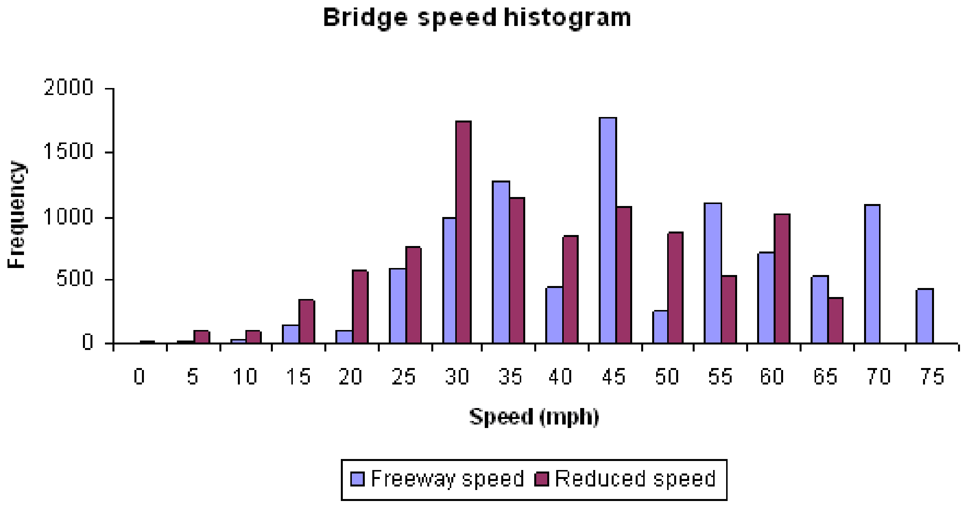


Figure 6.6. Variation in the reduction of bridge approach roadway speed

6.3.2 The value of travel time (VTT)

The next important variable in estimating user costs is the value of the user's time. It is assumed that the value of time is directly proportional to income of road users, and hence the attributed values of time change over time are in direct proportion to changes in income (GDP). Also, to account for inflation, using a base-year Consumer Price Index (CPI) model, the program year could be simulated as shown in Equation 6.5.

$$VTT_{year} = VTT_{base-year} \times \frac{CPI_{year}}{CPI_{base-year}} \tag{6.5}$$

Based on the sources indicated in Tables 6.6 to 6.8 below, information is provided on the distribution of hourly travel time values in 2009 dollars by vehicle class, the recommended travel time value based on the percentage of wages, and the average vehicle occupancy by vehicle classes. According to the Florida Standard Urban Transportation Modeling Structure (FSUTMS), in Florida, over 90% of vehicles have lone drivers, thus, 50% of wages is used from Table 6.6 as the value of time.

Table 6.6. Distribution of hourly travel-time values in 2009 dollars by vehicle class

	Vehicle class						
Category	Small Auto	Med-sized Auto	4-Tire Truck	6-Tire Truck	3- or 4-Axle Truck	4-Axle combination Truck	5-Axle combination Truck
Labor/fringe	$44.46	$44.46	$30.50	$37.04	$30.84	$37.15	$37.15
Vehicle productivity	$2.91	$3.42	$3.68	$5.20	$14.88	$12.56	$13.50
Inventory	$0.00	$0.00	$0.00	$0.00	$0.00	$2.79	$2.79
On-the-clock	$47.39	$47.89	$34.18	$42.24	$45.72	$52.50	$53.43
Off-the-clock	$24.21	$24.26	$25.53	$42.24	$45.73	$52.50	$53.45

Source: Updated from Forkenbrock and Wisbrod (2001)

Table 6.7. Values of travel time for personal and business travel

Transportation mode and trip purpose	value of time
AUTO	
Drive alone commute	50% of wages
Carpool drive commute	60% of wages
Carpool passenger commute	40% of wages
Personal (local)	50% of wages
Personal (intercity)	70% of wages
Business	100% of total compensation
TRANSIT BUS	
In vehicle commute	50% of wages
In vehicle personal	50% of wages
Excess (waiting)	100% of total compensation
Business	100% of total compensation
TRUCK	100% of total compensation

Source: ECONorthwest and Parsons (2002)

Table 6.8. Vehicle occupancy by classes

	Autos	Light Truck	Heavy Truck
Average vehicle occupancy	1.22	1.03	1.04

Source: AASHTO (2003)

The estimated value of travel time (VTT) can be calculated by vehicle classes (cars, trucks), i.e.

VTT = percentage of wage*average wage*vehicle occupancy (6.6)

6.3.3 Estimate of current traffic volume

In a multi-year simulation of user cost estimates, the traffic volume variable V_{ry} is forecast by interpolation for the year of the project from Pontis roadway data items as follows:

$$
\begin{aligned}
V_{ry} &= 0 && \text{if } V_{r0} \leq 0 \\
V_{ry} &= V_{r0} && \text{if } V_{rn} \leq 0 \text{ or } V_{r0} \leq 0 \text{ or } Y_{rn} \leq Y_{r0} \text{ or } Y \leq Y_{r0}
\end{aligned}
\qquad (6.7)
$$

$$V_{ry} = V_{r0} \times \left(\frac{V_{rn}}{V_{r0}}\right)^{\left(\frac{Y-Y_{r0}}{Y_{rn}-Y_{r0}}\right)} \qquad \text{otherwise}$$

Where:

V_{r0} is the most recent actual traffic volume estimate (NBI item 29, adttotal in the roadway table)

Y_{r0} is the year of most recent traffic volume estimate (NBI item 30, adtyear in the roadway table)

V_{rn} is the forecast future traffic volume (NBI item 114, adtfuture in the roadway table)

Y_{rn} is the year of forecast traffic volume (NBI item 115, adtfutyear in the roadway table)

Y is the current year of the program simulation

6.3.4 Total travel time cost

Total travel time (delay) cost can be estimated as follows:

$$\text{travel time cost} = \text{travel time value} \times \text{additional travel time} \times \text{ADT} \tag{6.8}$$

Based on the 5,435 bridges in the Florida bridge inventory, Figure 6.7 shows the histogram of the variation in the estimated total travel time costs at the bridges.

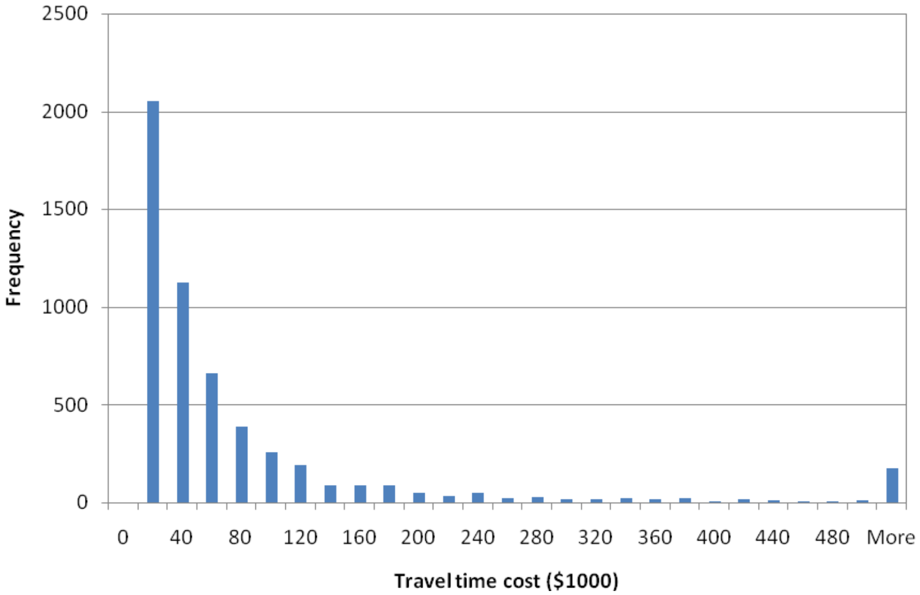


Figure 6.7. Histogram of estimated travel time cost

6.4. Vehicle operating costs (VOC)

The components of vehicle operating cost (VOC) are the individual items associated with vehicle operation on which expenses are directly incurred. These include the costs of energy needed to propel the vehicle, fluids, and other light consumables associated with mechanical working of the drive train, occasional replacement of the vehicle's contact surfaces with the guide-way, vehicle repair and maintenance, and vehicle depreciation. Table 6.9 shows the average vehicle operating cost by vehicle classes.

Table 6.9. Average vehicle operating costs (cents/vehicle mile)

	Fuel and oil	Maintenance and repair	Tires	Mileage-dependent Depreciation	Total
Small autos	7.45	4.83	0.69	19.18	32.15
Mid-size autos	8.89	5.69	2.18	17.25	34.00
Large autos	10.35	5.98	2.62	17.25	36.20
SUVs	11.51	5.98	2.18	16.56	36.23
Vans	10.35	5.69	2.33	16.56	34.93
Trucks	29.55	15.30	5.11	14.63	64.58

Source: costs are updated to 2009 from the following: nontruck fuel, maintenance and repair, and tires, AAA (2005); truck fuel, maintenance and repair, and tires, Barnes and Langworthy (2003); and depreciation estimations and projections are on the basis of data from FHWA (2002).

6.4.1 Fuel costs

Fuel is a key component of vehicle operating costs. For highway vehicles, fuel costs can account for 50 to 75% of the usage-related costs, and they can be estimated on the basis of fuel efficiency and unit fuel price. Generally, very low speeds, steep uphill grades, and curves lead to higher fuel consumption rates and hence higher overall fuel costs. In Table 6.10, the relationship between speed and fuel consumption is shown for both autos and trucks.

Table 6.10. Fuel consumption for cars and trucks (gallons per mile)

Speed (mph)	Autos	Trucks
5	0.117	0.503
10	0.075	0.316
15	0.061	0.254
20	0.054	0.222
25	0.050	0.204
30	0.047	0.191
35	0.045	0.182
40	0.044	0.176
45	0.042	0.170
50	0.041	0.166
55	0.041	0.163
60	0.040	0.160
65	0.039	0.158

Source: AASHTO (2003)

Typically when used for project evaluations, i.e., comparing existing situations to an alternative improvement or replacement project, changes in fuel costs due to a change in speed resulting from an improvement, can be calculated with Equation 6.9. The fuel consumption (gallons per mile) was shown earlier in Table 6.10 for various vehicle types and at different traveling speeds. Such changes in fuel costs between that of improvement project and the existing situation will be estimated using the difference between the approach roadway speed and the speed of travel on the bridge.

$$\Delta C(S)_{fuel} = (gal_{speed0} - gal_{speed1})P \tag{6.9}$$

Where: $\Delta C(S)_{fuel}$ = change in fuel costs as a function of speed (cents)

gal_{speed0} = gallons per mile for pre-improvement speed

gal_{speed1} = gallons per mile for post-improvement speed

P = fuel price per gallon (cents)

Fuel costs can also be expressed as a function of travel time, as shown in Table 6.11 in terms of the cost of fuel consumption per minute of delay. Although these factors are a function of delay, it should be noted that the fuel consumption is due primarily to acceleration of vehicles after being delayed, rather than fuel consumed idling during delay periods.

Table 6.11. Fuel consumption per min of delay (gallon/min)

Speed (mph)	Autos	Trucks
20	0.011	0.102
25	0.013	0.133
30	0.015	0.167
35	0.018	0.203
40	0.021	0.241
45	0.025	0.28
50	0.028	0.321
55	0.032	0.362
60	0.037	0.404
65	0.042	0.447
70	0.047	0.49
75	0.053	0.534

Source: AASHTO (2003)

Again, for evaluation of improvement projects, changes in fuel costs due to delay can be calculated by equation 6.10:

$$\Delta C(D)_{fuel} = (gal_{\min})(D_0 - D_1)P \tag{6.10}$$

Where: $\Delta C(D)_{fuel}$ = change in fuel costs as a function of delay (cents);

$gal_{\min}$ = gallons consumption per minute;

D_0 = average delay before improvement (minute);

D_1 = average delay after improvement (minute);

P = fuel price per gallon (cents);

6.4.2 Inventory costs of cargo

Inventory costs of cargo are sometimes incurred as user costs due to use of a truck shipping service. To calculate inventory costs on a per vehicle-mile basis, an hourly interest rate must be computed along with the amount of time it takes for the vehicle to travel a mile, using equation 6.11:

$$I(S) = 100 \times \frac{r}{8760} \times \frac{1}{S} \times P_{cargo} \tag{6.11}$$

Where: $I(S)$ = inventory costs (cents per vehicle-mile) as a function of speed;

r = interest rate, per annum;

P_{cargo} = value of the cargo (in dollars);

S = speed of the vehicle (mph).

To estimate the change in inventory costs due to travel speed change expected from an improvement project, equation 6.12 shows inventory costs per vehicle mile as a function of vehicle speed and cargo value.

$$\Delta I(S) = 100 \times \frac{r}{8760} \times (\frac{1}{S_0} - \frac{1}{S_1}) \times P_{cargo} \tag{6.12}$$

Where: $\Delta I(S)$ = change in inventory costs (cents per vehicle-mile);

S_0 = speed before the improvement (mph);

S_1 = speed after the improvement (mph);

The estimation of inventory cost associated with a change in delay is relatively straightforward. An improvement project that results in reduction of delay (rather than a change in speed) would have the following effect on inventory costs, as shown in Equation 6.13.

$$\Delta I(D) = 100 \times \frac{r}{8760 \times 60} \times P_{cargo} \times \Delta D \qquad (6.13)$$

Where: $\Delta I(D)$ = change in inventory costs (cents per minute);

ΔD = change in delay (minute)

The inventory cargo costs will be ignored in this study because the data are not available.

6.4.3 Speed-based changes in vehicle operating costs

Using the same variables defined above, changes in Vehicle Operating Costs (cents per vehicle-mile) due to inventory costs and fuel costs are estimated using the following two equations 6.14 and 6.15:

$$\Delta OC(S) = \Delta C(S)_{fuel} + \Delta I(S) \qquad (6.14)$$

$$\Delta OC(D) = \Delta C(D)_{\min} + \Delta I(D) \qquad (6.15)$$

6.4.4 Vehicle operating costs due to road surface condition

As mentioned earlier, roadway surface condition can influence travel time. To some extent, pavement surface roughness, often measured in terms of the present serviceability index (PSI) or international roughness index (IRI), can also affect the maintenance, tire, repair, and depreciation cost components of VOC. Figures 6.8 and 6.9 show the relation curve between the IRI and VOCs.

As also reported in Sinha and Labi (2009), Barnes and Langworthy (2003) developed adjustment factors for all VOC components combined, as a function of pavement surface roughness (Figure 6.5), assuming that:

- PSI 3.5 or better (IRI of about 80 in./mile) will have no impact on operating costs
- PSI of 2.0 or worse (IRI of about 170 in./mile) will add an extra cost of 1¢ per mile in maintenance and repair costs, or 2.5 ¢ cost per mile if we consider depreciation costs as well.

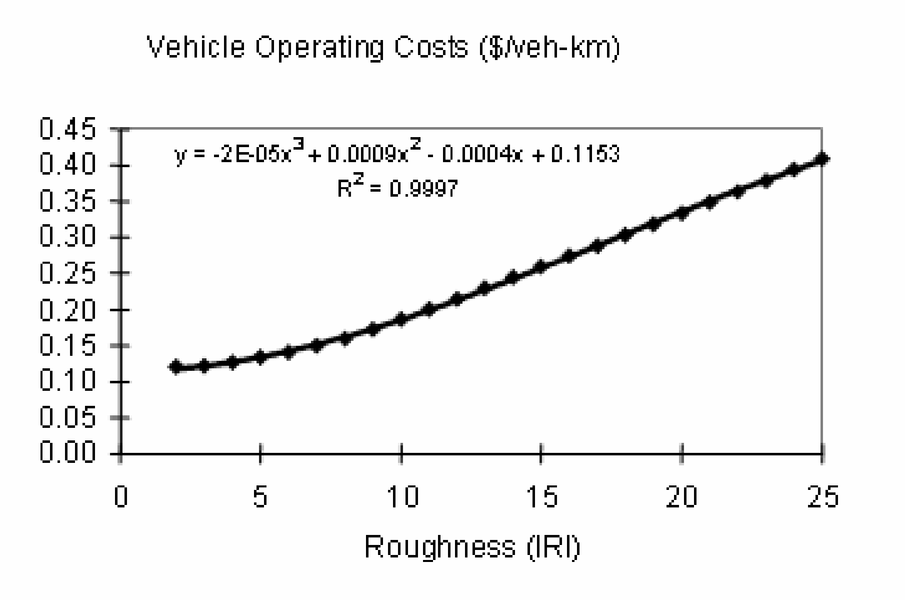


Figure 6.8. Relationship between IRI and VOC (Source: Labi and Sinha 2007)

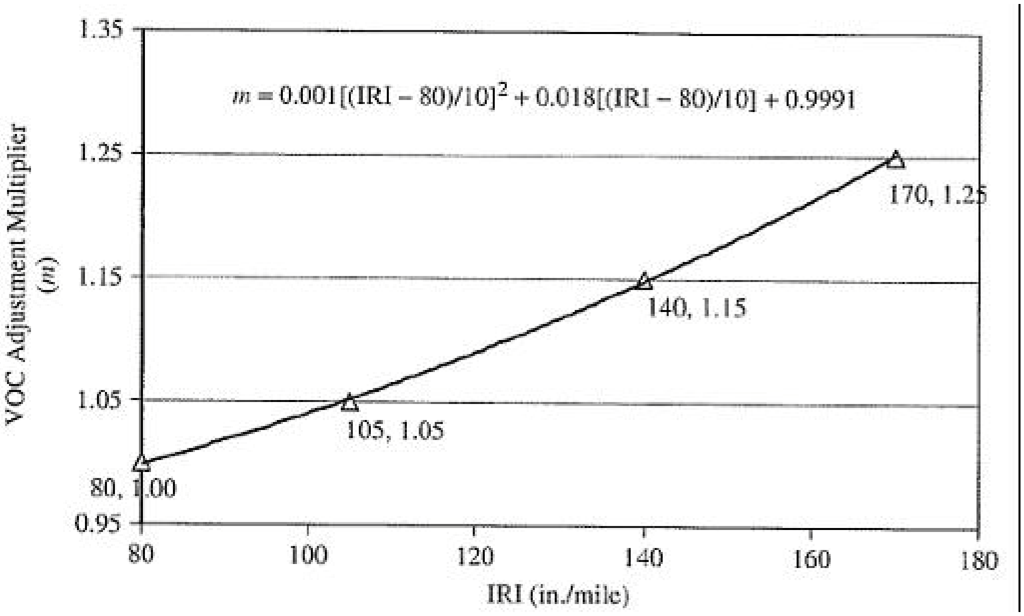


Figure 6.9. VOC adjustments for pavement roughness levels (Source: Sinha and Labi, 2007)

6.4.5 Total vehicle operating costs

The VOCs components have been presented above in various sections and the total VOCs can be estimated using equation 6.16, including a modification factor for the contribution of road surface roughness.

$$VOC = m \times (\Delta OC(S) \times L + \Delta OC(D) + others \times L) \qquad (6.16)$$

Where: m = adjustments for pavement roughness levels
$\Delta OC(S)$ = change in operating costs due to speed change (cents per vehicle mile);
$\Delta OC(D)$ = change in operating costs due to delay (cents);
$others$ = total costs of tires, repair and maintenance, and depreciation (cents per vehicle mile)
L = length of bridge (mile).

The result of vehicle operating costs estimated for the Florida bridge data is shown in Figure 6.10.

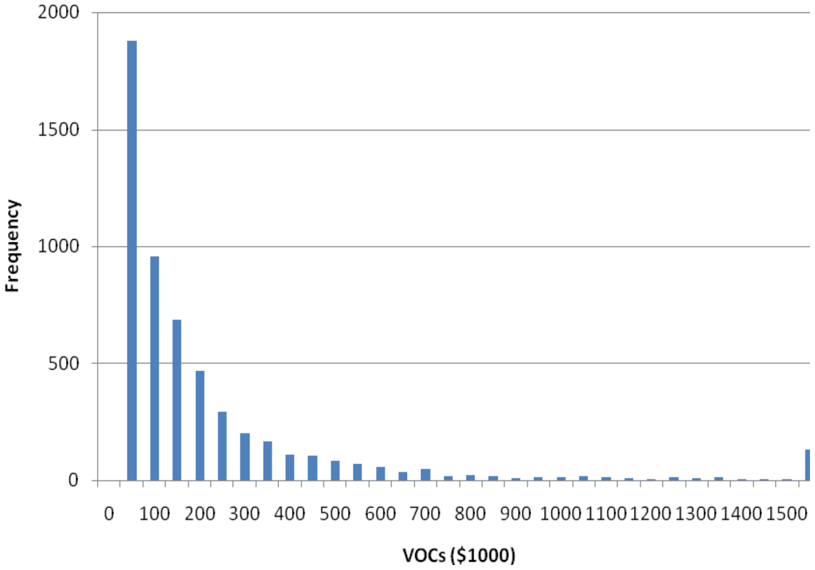


Figure 6.10. Histogram of vehicle operating costs on Florida bridges

6.5. Accident User Costs

The occurrence of accidents on the transportation network may be characterized by operational and safety deficiencies arising from inadequate bridge geometry, and the poor condition of bridge pavement surfaces. By improvement of safety-related engineering features on a bridge, crash reduction can be achieved, thus reducing accident user costs.

6.5.1 Accident rate estimation methods

Accident rates are sensitive to the number of lanes, direction of traffic, functional classification, speed, approach roadway width, and traffic volume. The accident rate can be estimated from actual accident studies when they exist. The following sections describe some previous studies related to accident rates on highways in general.

6.5.1.1 Urban area (AASHTO, 2003):

Accident frequency is a function of a variety of factors, including highway design features, traffic volumes, and congestion levels. In absence of more detailed information, accident frequency could be modeled as a function of the volume-capacity ratio, as shown in Equation 6.17 for application to urban freeways; this provides an approximation of the safety benefits of capacity improvements.

$$A_R = \frac{3.0234(\frac{V_1}{C_1}) - 1.11978(\frac{V_1}{C_1})^2}{3.0234(\frac{V_0}{C_0}) - 1.11978(\frac{V_0}{C_0})^2} - 1 \tag{6.17}$$

Where: A_R = proportional change in accident rate;

$\frac{V_0}{C_0}$ = flow/capacity ratio for urban freeway segment without improvement;

$\frac{V_1}{C_1}$ = flow/capacity ratio for urban freeway segment with improvement.

To use Equation 6.17 to estimate accident frequency change, it is necessary to have knowledge of the historical accident frequency, for both cases of before and after the improvement.

6.5.1.2 Rural area (AASHTO, 2003):

The Interactive Highway Safety Design Model (IHSDM) base model for rural road segments predicts the number of accidents based on traffic volumes and roadway features. The base model assumes the following features:

- 12 feet lane width;
- 6 feet shoulder width;
- Roadside hazard rating of three;
- Driveway density of five driveways per mile;
- No horizontal and vertical curvature;
- Level grade.

A series of accident reduction factors (Table 6.12) are also been incorporated into the model to account for road features that are different from the base model.
For rural area, the base model is:

$$A = \frac{AADT \times 365}{1{,}000{,}000} \times 0.6148 \times L \tag{6.18}$$

Where: A = predicted number of accidents on the bridge;
$AADT$ = annual average daily traffic volume on the bridge;
L = the length of bridge.

Table 6.12 Accident reduction factors for bridge improvement

Bridge improvement	Accident reduction factors (%)
Replacement	46
Widening	48
Deck repair	14
Rail upgrade	20

6.5.1.3 Highway segment based on alignment (Forkenbrock and Foster 1997)

The Urban and Rural models both have limitations, such as the inability to predict accident frequency in urban areas if the current accident frequency is unknown, or on rural roads if there is horizontal or vertical curvature. A third model could be used as an alternate method (equation 6.19) to estimate the accident rate based on the bridge alignment.

$$Y = e^{0.517 \times 0.972^{PSR} \times 1.068^{TOPCURV} \times 1.179^{PASSRES} \times 1.214^{ADTLANE} \times 0.974^{RIGHTSH} \times 0.933^{LANES} \times 1.051^{TOPGRAD}} \tag{6.19}$$

Where: Y = Accident rate in millions of VMT
PSR = present serviceability rating of the pavement surface ranging from 0 (failed) to 5 (excellent)
$TOPCUVR$ = the severity of the worst horizontal curve ranging from 0 (no curve) to 12 (sharpest curve)
$PASSRES$ = dummy variable representing the presence/absence of passing restrictions (1/0, 1 respectively)
$ADTLANE$ = hourly traffic volume in thousands per lane;
$RIGHTSH$ = right shoulder width (ft);
$LANES$ = dummy variable representing the number of lanes (1 for 4 lanes, 0 for 2 lanes);
$TOPGRAD$ = measure of the average vertical grade ranging from 0 (no grade) to 12 (severe grade).

6.5.1.4 Existing Florida accident (linear regression) model

An accident risk model was developed by Thompson (1999) using historical crash data, in which crashes at bridge sites are mentioned to be strongly affected by narrowness of the bridge (defined as the ratio of the number of lanes to the roadway width on the bridge), approach alignment, deck condition, functional classification, bridge length, traffic volume, and speed.

Tables 6.13 to 6.15 describe the data used in Thompson (1999)'s model, and the sources of the data, as well as the relationship between the data, and the model's statistical coefficients. The model can be used to estimate the number of accidents per year for a particular bridge.

Table 6.13. Data used in the existing Florida model (Thompson 1999)

Name	Description	Pontis Table	NBI Items	Range in data
funcclass	Functional class of roadway on bridge	roadway	26	1 to 19
lanes	Number of lanes on bridge	roadway	28A	1 to 12
length	Length of the bridge	bridge	49	1.8 to 10887.5 m.
appralign	Approach alignment rating	inspevnt	72	2-9 (missing=10)
roadwidth	Width of roadway on the bridge	roadway	51	3-58 meters
adttotal	Most recent average daily traffic count	roadway	29	1-295,000
adtyear	Year of most recent traffic count	roadway	30	1988-1998
adtfuture	Future traffic forecast	roadway	114	0-538,375
adtfutyear	Year of forecast	roadway	115	2015-2020
dkrating	Condition rating of deck	inspevnt	58	1-9 (missing=10)

Table 6.14. Intermediate variables

Name	Formula	Range in data set
UrbanArterial	funcclass=14 or 16	true or false
AlignLE6	appralign<=6	true or false
Narrowness	lanes/roadwidth	0.06-0.36
ADT	See section 2.3	1 to 324,806
BadDeck	dkrating<=6	true or false

Table 6.15. Model statistics

For bridge where	Variable	Coefficient	Std.Error	t value
UrbanArterial=false	Constant	-377.3701	66.0689	-5.7118
UrbanArterial=true	Constant	886.0098	109.9613	8.2835
All bridges	lanes*length	0.7323	0.0455	16.1039
AlignLE6=false and BadDeck=false	Narrowness*ADT	0.3904	0.0087	44.9273
AlignLE6=true and BadDeck=false	Narrowness*ADT	0.5031	0.0194	25.8690
AlignLE6=false and BadDeck=true	Narrowness*ADT	0.4531	0.0257	17.6592
AlignLE6=true and BadDeck=true	Narrowness*ADT	0.7899	0.0556	14.2052

6.5.2 Florida accident statistics and unit costs

According to the Florida Traffic Crash Statistics Report of 2007, Florida crash data for roadways (including bridges) from 1994 to 2006, indicated that fatal injuries were approximately 1.12% of all accidents, injuries were 58.93%, and ‘Property Damage Only’ or PDO crashes were 39.95% of all accidents (Table 6.16) (FDOT 2007). A more detailed breakdown for each year is shown in Tables 6.17 and 6.18.

Table 6.16. Accident proportion for Florida crash data

Accident type	Proportion (%)
Fatal	1.12
Injuries	58.93
Property damage only	39.95

Table 6.17. Accident counts and proportion in categories in Florida

	2006	**2005**	**2004**	**2003**	**2002**	**2001**	**2000**
Fatal	3,084	3,185	2,936	2,880	2,816	2,717	2,733
Injury	137,282	147,879	142,388	138,891	142,992	145,208	144,096
PDO	115,834	117,541	107,578	101,523	104,662	108,244	99,712
Total	256,200	268,605	252,902	243,294	250,470	256,169	246,541
%Fatal	1.20%	1.19%	1.16%	1.18%	1.12%	1.06%	1.11%
%Injury	53.58%	55.05%	56.30%	57.09%	57.09%	56.68%	58.45%
%PDO	45.21%	43.76%	42.54%	41.73%	41.79%	42.25%	40.44%

Table 6.17. Accident counts and proportion in categories in Florida (continued))

	1999	1998	1997	1996	1995	1994	Average
Fatal	2,625	2,605	2,542	2,550	2,586	2,450	2,747
Injury	143,172	149,315	148,305	149,565	143,839	135,187	143,701
PDO	97,612	93,520	89,792	89,262	82,164	68,546	98,153
Total	243,409	245,440	240,639	241,377	228,589	206,183	244,601
%Fatal	1.08%	1.06%	1.06%	1.06%	1.13%	1.19%	1.12%
%Injury	58.82%	60.84%	61.63%	61.96%	62.92%	65.57%	58.93%
%PDO	40.10%	38.10%	37.31%	36.98%	35.94%	33.25%	39.95%

The unit monetary cost of the risk of death, injury, or property damage resulting from accidents, is a function of market or economic costs, which include property damage, insurance and legal costs, medical costs, and lost productivity, and nonmarket costs, the emotional and social costs of casualties resulting from road crashes (Lindberg and Borlange 1999; Miller et al. 2000).

The literature on traffic safety provides two different perspectives on the economic consequences of accidents:

- The Human Capital method measures only market costs (property damage, medical treatment, and lost productivity). This typically places the value of saving a human life at $0.5-1 million, with lesser values for injuries.
- The Comprehensive approach adds non-market costs, including pain, grief, suffering, and reduced quality of life, as reflected by people's willingness-to-pay (WTP) for increased safety (i.e., reduced risk of crashes and reduced crash damages), or willingness-to-accept increased crash risk and damages.

The WTP approach is a more appropriate measure of the true cost to society of crashes, and the appropriate value to use when assessing crash prevention. Using the WTP approach, Lindberg and Borlange (1999) concluded that the nonmarket cost component was the dominant component and overshadows all other cost components of highway crashes: the nonmarket costs account for 90% for fatal, 80% for severe injury, and 60% for light injury crash costs.

One commonly used source for the dollar value estimates of crashes is the annual publication of the National Safety Council (NSC) estimates (NSC, 2001). Also, the cost of road crashes can be based on a weighted injury scale by using indices to the level of severity of the road crash. The unit costs of each crash severity type are available for injury scales such as the KABCO rating scale, an acronym based on the code for each severity class of the injury (NSC 2001). Table 6.18 shows the unit crash cost values for the KABCO crash coding scheme, updated using inflation factors from the FDOT transportation costs reports (FDOT, 2009). Injury costs for Florida are based on the work of Blincoe (1994), converted to the KABCO injury system based on medical descriptions of injuries in the Blincoe's original data set. The data was then updated to 2009 dollars using the Consumer Price Index. All unit costs are listed as Willingness-to-Pay except for the property damage only cost.

Table 6.18. Unit crash costs (2009 dollars) on the basis of the KABCO Injury Scale

Code	Severity	Unit Cost (Nationwide)#	Unit Cost (FL)*	Human Capital Cost (FL)##
K	Fatal	5,042,933	5,215,128	14,268
A	Incapacitating	250,161	365,921	10,825
B	Injury Evident	64,367	79,454	8,430
C	Injury Possible	30,637	51,630	6,006
O	Property Damage Only	2,920	N/A	3,425

Source: Updated from #NSC (2001), *Thompson (1999), ##CAR database (bridge site crashes)

Human Capital costs were calculated based on the Florida crash reports. According to the FDOT CAR's database, a total of 13,422 accidents occurred on Florida Highway Bridges in 2003, 14,571 accidents in 2004, 15,600 accidents in 2005, 14,838 accidents in 2006, and 14,324 accidents in 2007. From these records, human capital costs can be estimated for each severity level of roadway accident, as shown in the following Tables 6.19 to 6.23, and Figures 6.11 to 6.15.

Table 6.19 and Figure 6.11 show statistical data for "Property Damage Only" accidents. The high skewness and kurtosis, indicate that the median value, rather than the mean value, is probably more appropriate to represent these data.

Table 6.19. Injury level 1-None injury costs, property damage only (2009 dollars)

	2003*	2004*	2005*	2006*	2007*	Nationwide#
Mean	5544.331	5426.639	5311.438	4978.333	4690.42	
Standard Error	95.96309	84.69335	97.56696	88.36006	90.38822	
Median	3519	3750	3450	3075	3330	2920
Mode	3060	3000	2760	2460	2220	
Standard Deviation	7506.007	7209.39	8641.151	7767.649	7822.107	
Sample Variance	36823619	34650199	54108321	49053954	55121939	
Kurtosis	181.4941	200.2758	655.9078	780.3871	971.3745	
Skewness	8.966907	9.610414	18.00521	19.60361	23.09288	
Range	229347	227100	398682	371952	396159	
Minimum	153	150	138	123	111	
Maximum	229500	227250	398820	372075	396270	
Sum	33920219	39321425	41662922	38472561	35126553	
Count	6118	7246	7844	7728	7489	

Source: Updated from *Florida CAR database (bridge site crashes), and #NSC (2001),

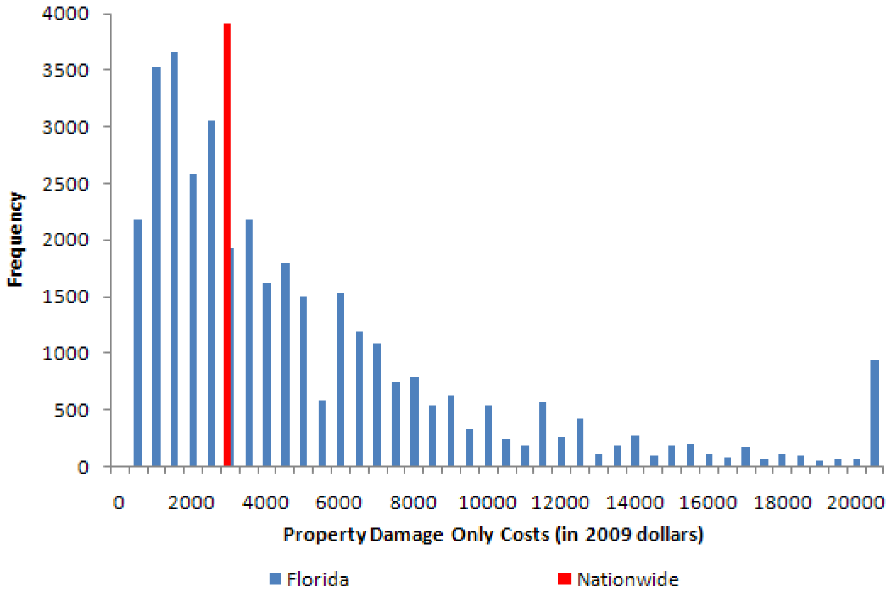


Figure 6.11. Histogram of 2003-2007 Property Damage Only Costs (in 2009 dollars)

Table 6.20 and Figure 6.12 show statistical data for injury accidents, using the "Human Capital" approach. This is compared with the "Willingness to Pay" approach in the rightmost two columns, for the nation and for Florida. The median value of the human capital approach is about $6,000. However, people in Florida are willing to pay $51,630 to prevent this type of bridge accidents, much higher than the nationwide estimated cost of $30,637.

Table 6.20. Injury level 2-Possible injury costs (2009 dollars)

	2003*	2004*	2005*	2006*	2007*	Nationwide[#]	Florida[##]
Mean	8665.828	8702.918	8185.803	8145.47	7642.176		
Standard Error	161.7992	175.7557	152.8437	147.4194	133.1424		
Median	6120	6000	6210	6150	5550	30,637	51,630
Mode	7650	7500	6900	6150	5550		
Standard Deviation	9884.326	10732.61	9683.589	8974.438	7923.932		
Sample Variance	63856149	76792662	67950655	65480115	56566401		
Kurtosis	69.03407	146.8504	325.6074	51.3534	50.39268		
Skewness	5.917068	8.755881	11.78779	5.35174	4.941755		
Range	183447	239850	331062	124107	138639		
Minimum	153	150	138	123	111		
Maximum	183600	240000	331200	124230	138750		
Sum	32340871	32453183	32857812	30187111	27068589		
Count	3732	3729	4014	3706	3542		

Source: Updated from [*]Florida CAR database (bridge site crashes), [#]NSC (2001), and [##] Thompson (1999).

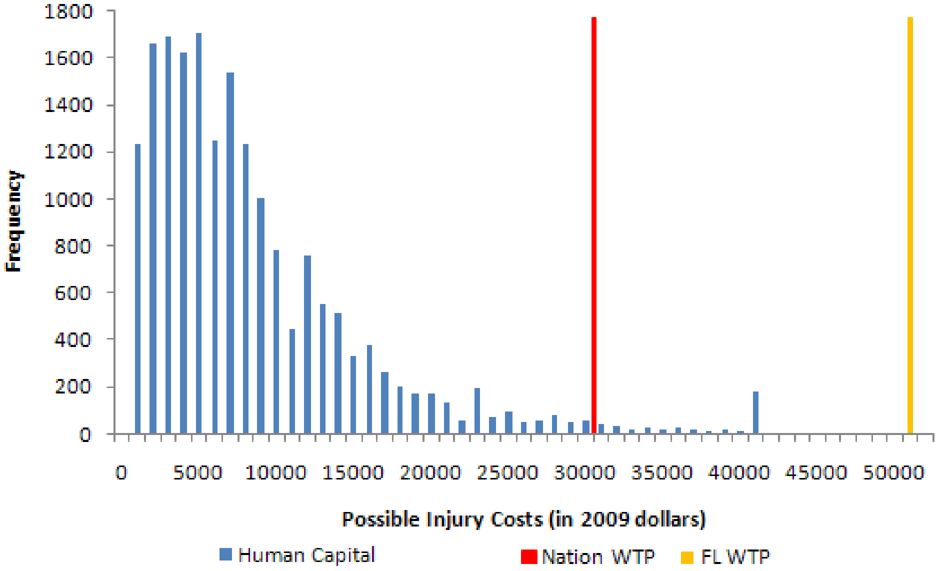


Figure 6.12. Histogram of 2003-2007 Possible Injury Costs (2009 dollars)

Table 6.21 and Figure 6.13 show statistical data for Non-incapacitating injury accidents. The median value of the human capital approach is about $8,000. However, people in Florida are willing to pay $79,454 to prevent this type of bridge accidents, which is $15,000 higher compared to the national estimate of $64,367.

Table 6.21. Injury level 3-Non-incapacitating costs (2009 dollars)

	2003*	2004*	2005*	2006*	2007*	Nationwide[#]	Florida[##]
Mean	12157.18	11767.49	11901.26	10904.04	10828.38		
Standard Error	342.1193	242.2368	359.3215	280.654	287.597		
Median	8721	9000	8280	7380	7770	64,367	79,454
Mode	6120	9000	13800	6150	11100		
Standard Deviation	16368.18	11705.33	17868.8	13232.47	13489.49		
Sample Variance	1.75E+08	91343111	2.31E+08	1.42E+08	1.64E+08		
Kurtosis	277.1284	34.45159	361.0539	231.5285	218.7611		
Skewness	12.25051	4.056431	15.28111	10.28428	10.72283		
Range	458847	190350	495282	362727	346209		
Minimum	153	150	138	123	111		
Maximum	459000	190500	495420	362850	346320		
Sum	27827778	27477084	29431812	24239675	23822437		
Count	2289	2335	2473	2223	2200		

Source: Updated from [*]Florida CAR database (bridge site crashes), [#]NSC (2001), and [##] Thompson (1999).

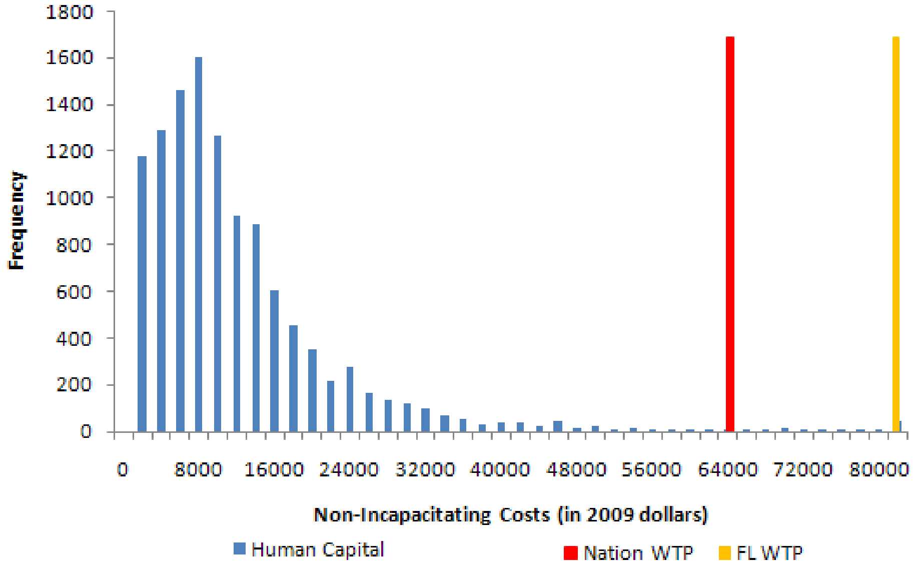


Figure 6.13. Histogram of 2003-2007 Non-Incapacitating Costs (2009 dollars)

Table 6.22 and Figure 6.14 show statistical data for Incapacitating Injury accidents. The median value of the human capital approach is about $11,000. However, people in Florida are willing to pay $365,921 to prevent this type of bridge accidents, which is more than the national estimate.

Table 6.22. Injury level 4-Incapacitating costs (2009 dollars)

	2003*	2004*	2005*	2006*	2007*	Nationwide[#]	Florida[##]
Mean	16768.71	15479.28	14868.13	13801.26	13243.66		
Standard Error	881.6894	567.854	427.0371	591.0298	599.5561		
Median	12240	11400	11040	10455	8991	250,161	365,921
Mode	15300	15000	13800	12300	5550		
Standard Deviation	27839.61	17640.07	13286.28	17897.57	17220.94		
Sample Variance	5.07E+08	2.07E+08	1.28E+08	2.6E+08	2.67E+08		
Kurtosis	245.4035	53.49271	7.951053	91.31598	50.00852		
Skewness	12.86884	5.436908	2.295289	7.778279	5.904739		
Range	621027	263850	96462	270477	210789		
Minimum	153	150	138	123	111		
Maximum	621180	264000	96600	270600	210900		
Sum	16718406	14937504	14392346	12655753	10926016		
Count	997	965	968	917	825		

Source: Updated from [*]Florida CAR database (bridge site crashes), [#]NSC (2001), and [##] Thompson (1999).

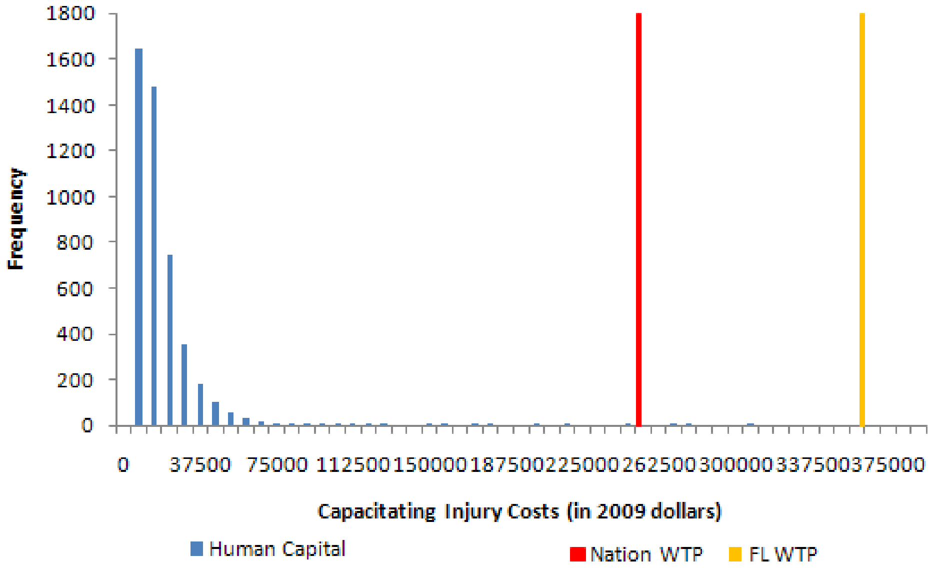


Figure 6.14. Histogram of 2003-2007 Incapacitating costs (2009 dollars)

Table 6.23 and Figure 6.15 show statistical data for Fatality accidents. The median value of the human capital approach is about $14,500. However, people in Florida and the nation are willing to pay about $5 million to prevent this type of roadway accidents, including pain and suffering, loss of enjoyment of life, and the premium associated with risk aversion. Here again, for bridge management, where the decision topic is the expenditure of public funds to prevent accidents, the WTP approach would seem most suitable.

Table 6.23. Injury level 5-Fatality costs (2009 dollars)

	2003*	2004*	2005*	2006*	2007*	Nationwide[#]	Florida[##]
Mean	23827.97	20546.71	26848.39	23197.46	50912.16		
Standard Error	2248.224	2231.247	3836.32	3017.951	33413.01		
Median	16218	15000	14076	13837.5	12210	5,042,933	5,215,128
Mode	12240	15000	13800	6150	11100		
Standard Deviation	25435.76	24846.12	46828.26	33606.48	380966.9		
Sample Variance	4.23E+08	4.12E+08	1.59E+09	9.18E+08	1.31E+11		
Kurtosis	10.07104	14.4256	47.29765	21.65891	129.2137		
Skewness	2.814678	3.415	6.076496	4.104343	11.35103		
Range	152235	163050	444222	256332	4354697		
Minimum	153	150	138	123	111		
Maximum	152388	163200	444360	256455	4354808		
Sum	3049980	2547792	4000410	2876485	6618580		
Count	128	124	149	124	130		

Source: Updated from [*]Florida CAR database (bridge site crashes), [#]NSC (2001), and [##] Thompson (1999).

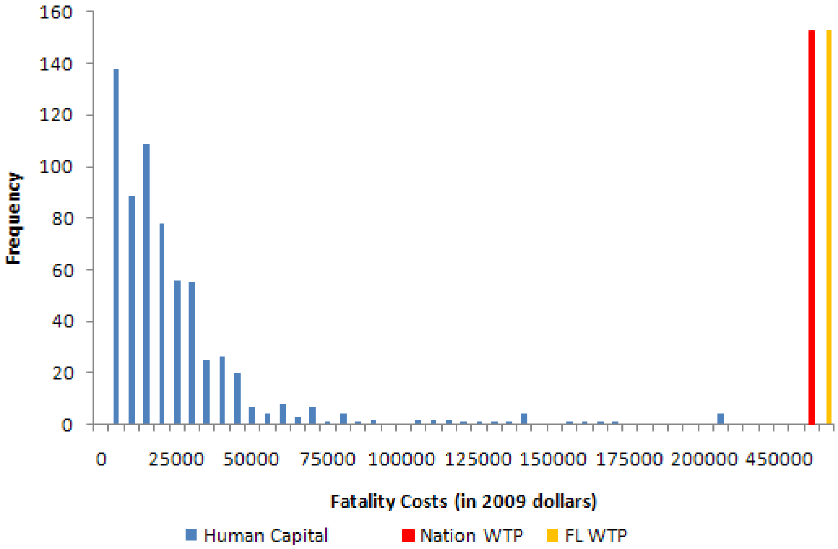


Figure 6.15. Histogram of 2003-2007 Injury level 5-Fatality Costs (in 2009 dollars)

6.5.3 Estimated accident user costs

Based on the Thompson (1999) study's linear regression model discussed above, accident rates were calculated as well as accident-related user costs. Figure 6.16 shows the histogram of estimated accident counts for the bridge inventory while Figure 6.17 shows the accident user costs.

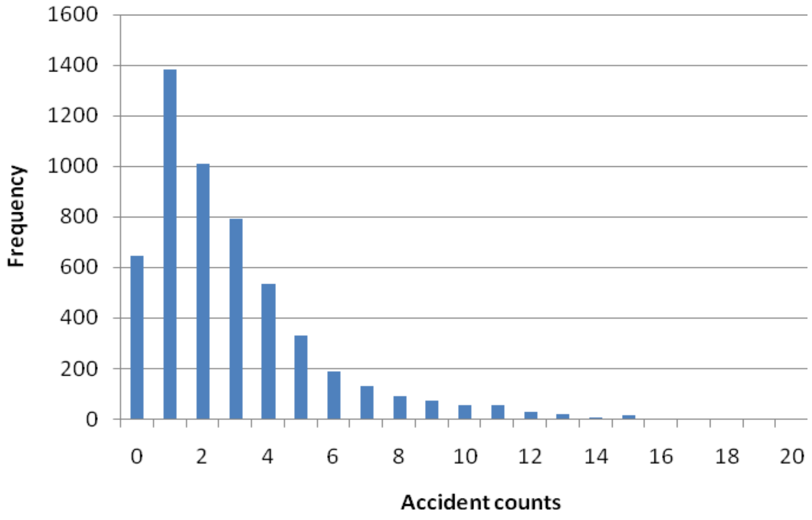


Figure 6.16. Histogram of estimated accident counts

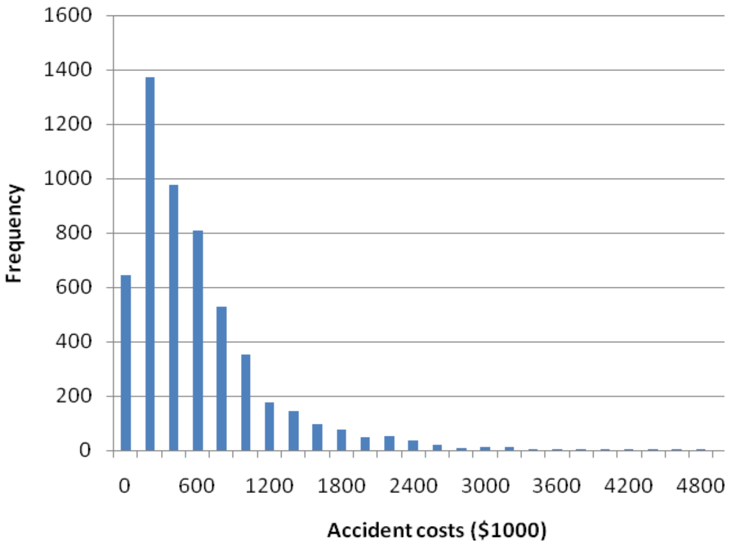


Figure 6.17. Histogram of accident costs

6.6. Florida Bridge User Costs

As discussed above, three main components of bridge user cost are travel time costs, vehicle operating costs, and accident costs. Figure 6.18 shows a histogram of user costs estimated for the 5,435 Florida bridges, using the existing accident cost model. The national cost data was utilized, as it used the willingness-to-pay approach, and was thus more realistic. If we look into each component, accident costs make the most contribution to user cost, as shown Figure 6.19. Therefore, prediction of bridge accident counts becomes more significant in user cost estimation.

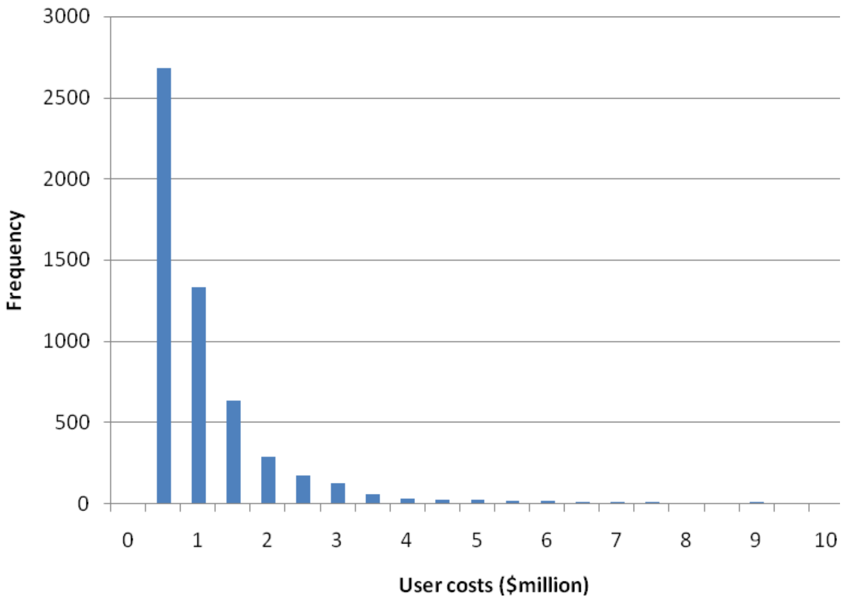


Figure 6.18. Histogram of Florida State Highway bridges user costs (in 2005dollars)

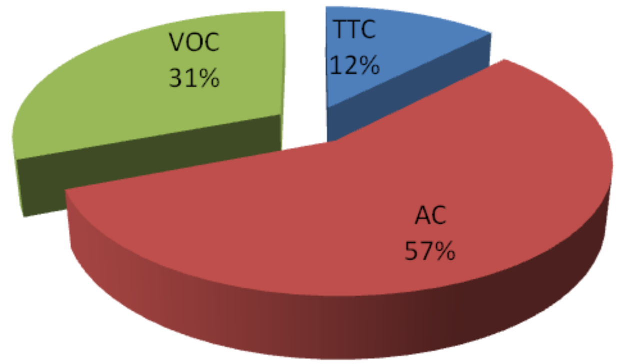


Figure 6.19. Total user costs by type: Travel Time Cost (TTC); Vehicle Operating Cost (VOC); and Accident Cost (AC)

6.7. Study on the Florida Bridge Accident Model

In estimating user costs, it has been seen that accident costs constitute a significant portion, but it is a challenge to accurately predict these costs related to potential accidents on a bridge. The following section presents the researchers' efforts to improve on the existing linear regression model for prediction of accident rates at bridges and also for estimating the related user costs.

6.7.1 Model formulation: dependent variable

Accident risk in the literature is expressed as accidents per 100 million vehicle miles, which assumes that the number of accidents is a direct multiple of traffic volume and segment length. However, Thompson (1999) argued that this could be problematic for bridges. The nature of bridge accidents is that the driver is suddenly presented with a new set of fixed obstacles to avoid, or a lack of escape routes to be used in order to avoid a collision with another vehicle. This suggests that accidents are more associated with a point on the network rather than a segment of road. . Therefore, Thompson (1999) suggested using annual accidents per million ADT to express accident rates, abbreviated as "aamdv", meaning annual accidents per million daily vehicles.

Figure 6.20 shows the crash data for years 2003 to 2007, indicating that more than 50% of state highway bridges have no crashes each year. The distribution of accident counts is heavily skewed toward zero, i.e., does not resemble a normal distribution. This violates the assumption for normal linear regression models. On the other hand, if only the non-zero crash data is considered, the log function of annual accidents per million ADT, shown in Figure 6.21, resembles a tradition bell-shaped normal distribution assumed for regression models.

Figures 6.22 to 6.25 also show the geographical locations of Florida State highway bridges and the associated crashes. Apparently, bridges in urban areas experience crashes more frequently than rural bridges. Looking at Figure 6.22, the following urban areas can be clearly seen as experiencing crashes at a consistently high rate through the five year period from 2003 to 2007: Jacksonville, Orlando, Miami-Fort Lauderdale, and Tampa-St. Petersburg areas.

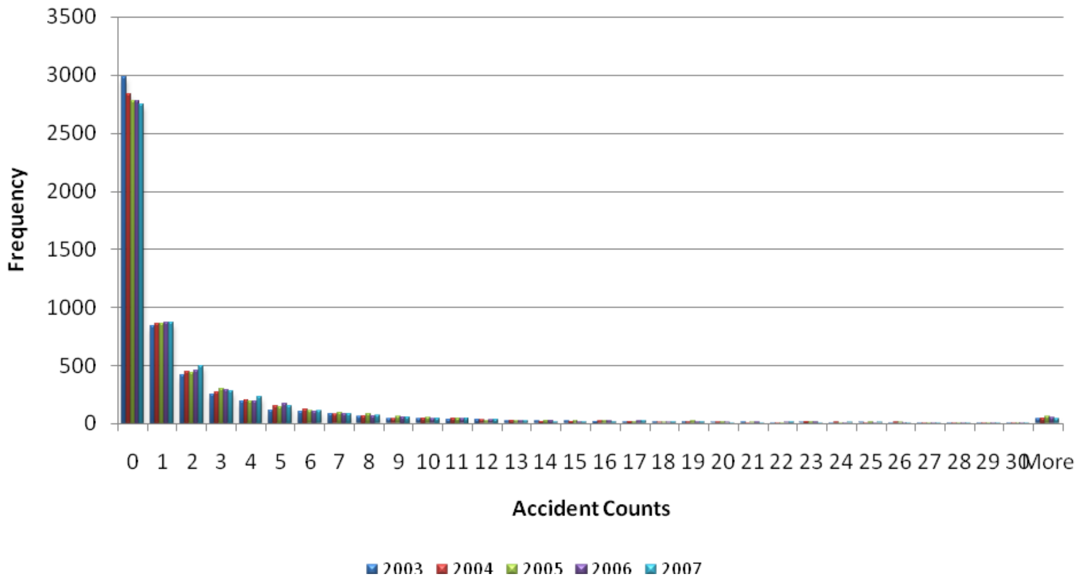


Figure 6.20. Frequency distribution of accident counts 2003-2007

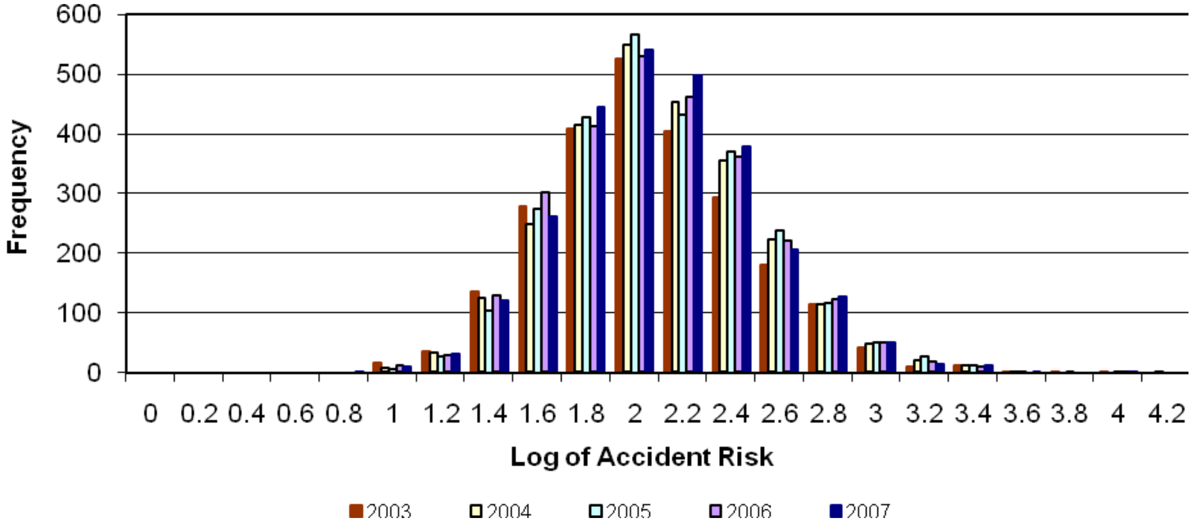


Figure 6.21. Frequency distribution of log accident risk 2003-2007

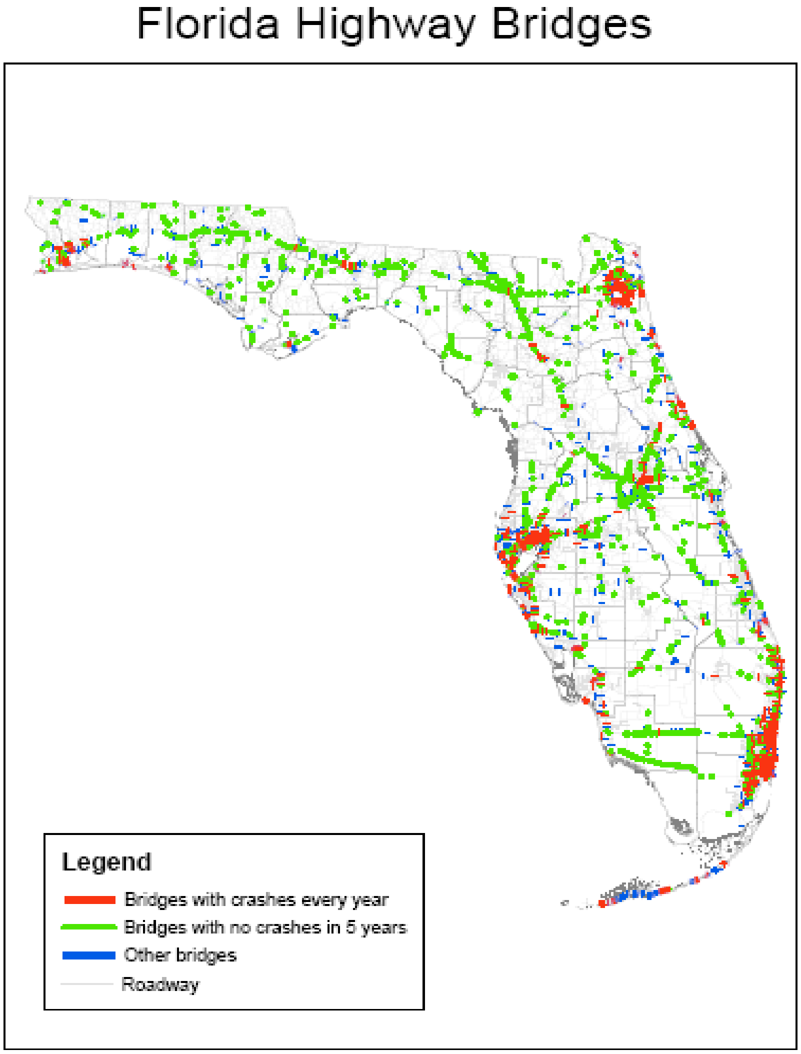
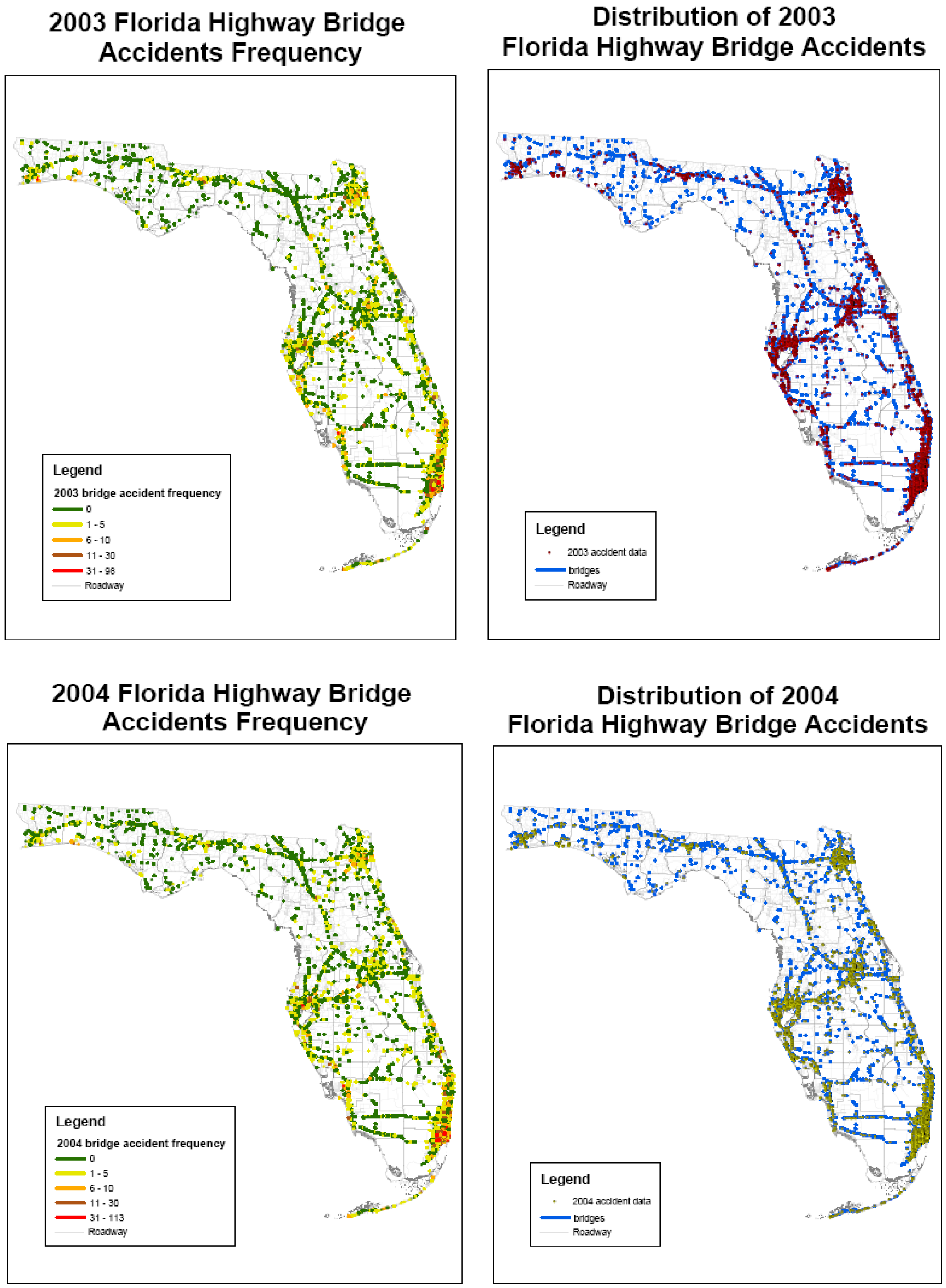


Figure 6.22. Florida highway bridges based on accident frequency for 2003 to 2007



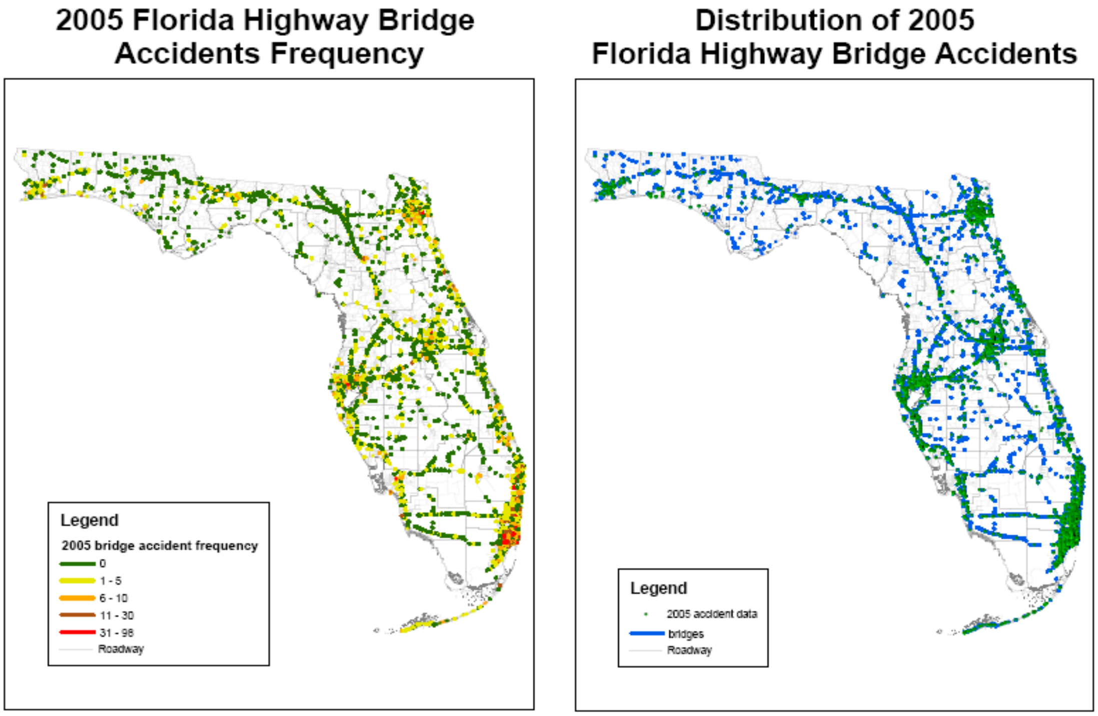
2003 Florida Highway Bridge Accidents Frequency

Distribution of 2003 Florida Highway Bridge Accidents

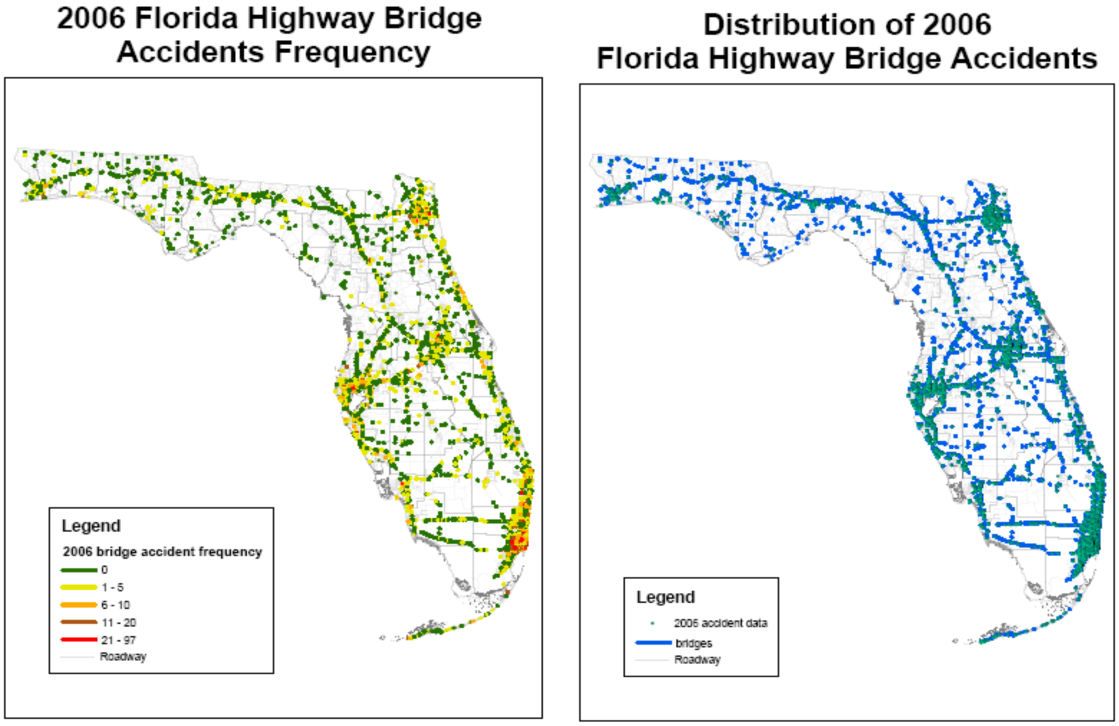
2004 Florida Highway Bridge Accidents Frequency

Distribution of 2004 Florida Highway Bridge Accidents

Figure 6.23. Florida highway bridges based on accident frequency for 2003 to 2004


2005 Florida Highway Bridge Accidents Frequency

Distribution of 2005 Florida Highway Bridge Accidents


2006 Florida Highway Bridge Accidents Frequency

Distribution of 2006 Florida Highway Bridge Accidents

Figure 6.24. Florida highway bridges based on accident frequency for 2005 to 2006

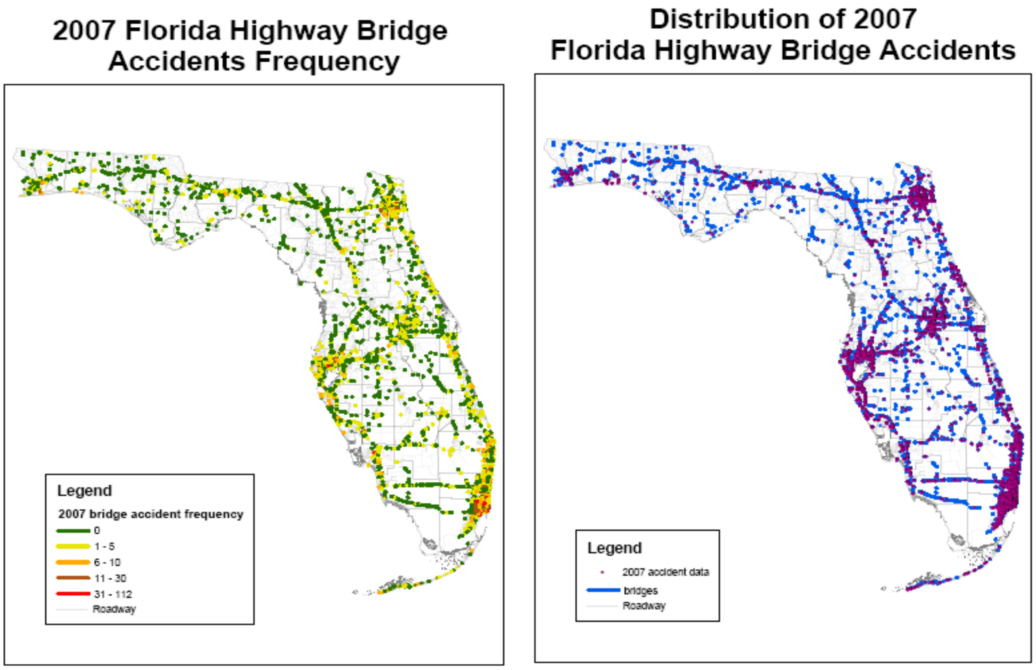


Figure 6.25. Distribution of bridge accidents and accident frequency for 2007

6.7.2 Model formulation: independent variable

Following the methodology of Thompson (1999), it is necessary to test elements of this intuitive model, using correlation analysis or hypothesis testing, to see if they have any statistical significance and to learn more about the relationship.

6.7.2.1 Narrowness

Narrowness is defined by Thompson (1999) as a relationship between roadway width and number of lanes. This variable describes the reduced availability of escape paths on a narrow bridge, the increased likelihood of side-swiping the guardrail, and the possibility of bouncing off the guardrail into another vehicle. Many possible ratios were considered as an expression of the narrowness. A correlation analysis was performed between accident risk and the various definitions of narrowness, as follows, and the correlation coefficients indicated in the parentheses: Number of lanes divided by roadway width (14.7%); Roadway width divided by number of lanes (-9.74%); ADT divided by Roadway width (1.89%); ADT divided by Lane width (6.64%); and Number of lanes multiplied by lengths divided by roadway width (10.9%). The result showed that narrowness, defined as the number of lanes divided by roadway width has the highest correlation coefficient (14.7%) compared to other defined variables. In the bridge data, the values of narrowness according to this definition range from 0.06 to 0.73.

Table 6.24 shows the distribution of average accident risk at bridges classified based on their narrowness. This confirms that narrow bridges are twice as likely to have accidents as wide bridges. Table 6.25 shows the distribution of bridges in terms of an inverse definition of the narrowness, i.e., roadway width divided by number of lanes. Unexpectedly, there is no such evident data to describe the relationship between accident risk and this definition of the narrowness variable.

Table 6.24. Summary of average accident risk at bridges categorized by narrowness

	2003	2004	2005	2006	2007	No. of bridges
Narrowness < =0.1745 (wide bridges)	52	55	69	54	60	2701
Narrowness >0.1745 (narrow bridges)	91	103	104	101	99	2734

Table 6.25. Summary of average accident risk at bridges categorized by inverse of narrowness

Roadway width divided by number of lanes	>=7.5	6.75-7.5	6.0-6.75	5.25-6.0	4.5-5.25	3.75-4.5	< 3.75	Total
No. of bridges	398	169	1875	1067	1000	742	184	5435
Average accident risk in 2003	98	39	44	62	82	113	172	72
Average accident risk in 2004	81	51	50	67	91	128	211	79
Average accident risk in 2005	107	54	63	72	92	128	202	87
Average accident risk in 2006	64	56	50	72	90	129	171	78
Average accident risk in 2007	69	57	57	71	90	118	186	80

6.7.2.2 Funnel

If the roadway narrows at the entrance to the bridge, then it is defined as a “funnel zone,” defined as approach roadway width divided by roadway width. Based on the bridge data, the range of funnel was found to be from 0.23 to 3.15. Table 6.26 shows the distribution of the estimated accident risk relative to the funnel zone. Correlation analysis indicates funnel has only 4.18% correlation to accident risk, thus there is no obvious relationship between funnel zone and accident risk.

Table 6.26. Summary of average accident risk at bridges categorized by funnel zone

	2003	2004	2005	2006	2007	No. of bridges
Accident risk at funnel zone	88	97	107	94	94	2887
Accident risk at Non-funnel zone	54	59	64	59	63	2548

6.7.2.3 Approach alignment

Approach alignment is an NBI Item data recorded for evaluation of the alignment of approach roadways to bridges. Table 6.27 shows the distribution of accident risk based on the approach alignment. There is no evident relationship between these data. According to FHWA(2005), an approach alignment rating of 6 is the highest rating where safe travel speeds are affected. If the bridge data set is separated into two groups (approach alignment rating is larger than 6 or not), the average risk in the first category is 68 aamdv, and in the second is 140 aamdv. This difference in mean accident risk is significant at the 90% confidence level.

Table 6.27. Summary of average accident risk at bridges categorized by approach alignment

Approach alignment (NBI) rating	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
No. of bridges	3	3	9	54	184	386	2667	2125	4
Average accident risk in 2003	57	151	168	219	118	94	70	62	11
Average accident risk in 2004	152	202	273	118	132	103	73	76	151
Average accident risk in 2005	38	162	359	294	102	111	83	79	0
Average accident risk in 2006	196	126	380	106	112	104	77	68	138
Average accident risk in 2007	114	227	534	123	121	97	77	73	11
Average accident risk	111	174	343	172	117	102	76	72	62

6.7.2.4 Deck condition

Table 6.28 shows the distribution of accident risk based on the deck rating, another NBI data item, representing the physical condition of the bridge deck. It is noticed that when deck rating is smaller than 6, accident risk is relatively high. According to FHWA(2005), a deck rating of 6 is the first where minor deteriorations is evident. If the data set is separated into two groups (approach alignment rating is larger than 6 or not), the average risk in the first category is 70 aamdv, and in the second was 86 aamdv; the difference in mean accident risk was significant at the 95% confidence level.

Table 6.28. Summary of average accident risk at bridges categorized by deck rating

Deck (NBI) rating	1	4	5	6	7	8	9	10
No. of bridges	1	17	121	478	3732	970	98	18
Average accident risk in 2003	143	98	109	80	65	88	97	3
Average accident risk in 2004	143	107	122	89	73	91	120	10
Average accident risk in 2005	122	112	120	96	80	104	97	7
Average accident risk in 2006	82	76	108	94	75	81	71	12
Average accident risk in 2007	41	139	113	82	77	84	78	6
Average accident risk	106	106	114	88	74	90	93	8

6.7.2.5 Functional classification

Table 6.29 shows the distribution of accident risk based on the functional class. It is noticed that functional class could affect accident risk, especially with classes 11, 12, 14 and 16.

Table 6.29. Summary of average accident risk at bridges categorized by functional class

Functional class	1	2	6	7	8	9	11	12	14	16	17	19
No. of bridges	582	851	301	92	64	75	992	1092	828	392	126	40
Average accident risk in 2003	37	47	48	22	0	0	100	60	113	125	35	0
Average accident risk in 2004	41	52	61	10	0	0	110	7	117	141	42	0
Average accident risk in 2005	44	53	64	41	0	0	132	86	116	136	33	0
Average accident risk in 2006	46	46	59	12	0	0	107	73	113	133	52	0
Average accident risk in 2007	49	51	69	10	0	0	108	79	108	125	54	0
Average accident risk	43	50	60	19	0	0	111	61	113	132	43	0

6.7.3 Model formulation: regression model

The previous sections have been used to narrate and formulate models similar to the existing bridge user cost model. The following sections present the efforts in this study to revise existing models or develop new accident models.

6.7.3.1 Linear regression

Following Thompson (1999)’s methodology, a linear regression model was chosen as a preliminary model. Using the bridge crash data for years 2003 through 2006, this linear regression model was formulated and used to predict the 2007 accident rates. The data did not show a strong linear relationship between accident risk and each of the following variables: approach alignment, the deck rating, and the functional class. The next step was to create a binary variable for each of these three independent variables. For approach alignment and deck ratings, values of 6 or less were grouped as poor conditions, while values of 7 or more were grouped as good conditions. Bridges on functional class 11, 14, and 16 roadways appear to have higher accident risks; this information was used to divide the data into two classes. Table 6.30 shows the result of the regression model. Please note that coefficients are expressed in thousands for convenience. In an approach similar to that of Thompson (1999), the variables are listed and separated under the following scenarios: F0: Functional class other than 11, 14, and 16; F1: Functional class equal to 11, 14, and 16. The narrowness x ADT variable is applied under the following possible scenarios: AppralignLE6=false and DkratingLE6=false; AppralignLE6=true and DkratingLE6=false; AppralignLE6=false and DkratingLE6=true; and AppralignLE6=true and DkratingLE6=true.

Table 6.30. Linear regression model statistics based on 2003-2006 data

For bridges where	Variable	Coefficient (×1000)	Std.Error	t-value	p-value
All Bridges	Constant	--579.65	0.04780	-12.13	0.000
Urban Arterial=true	Constant (x F1)	65.10	0.07228	8.92	0.000
All Bridges	Lanes × Length	0.89575	0.00003049	29.38	0.000
AppralignLE6=false and DkratingLE6=false	Narrowness × ADT	0.49274	0.00000567	86.87	0.000
AppralignLE6=true and DkratingLE6=false	Narrowness × ADT	0.43323	0.00003026	14.32	0.000
AppralignLE6=false and DkratingLE6=true	Narrowness × ADT	0.49427	0.00001071	46.15	0.000
AppralignLE6=true and DkratingLE6=true	Narrowness × ADT	0.82017	0.00008858	9.26	0.000

R-Sq = 34.8%

The regression model predicted the average accident frequency for 2007 as 2.64, with a range from -0.538 to 50.474, compared to the actual average value of 2.622, and range of 0 to 112. The coefficient of determination (R^2) of the prediction model is 0.348 and the average residual is -0.283 with a range from -34.0 to 102.7.

6.7.3.2 Logistic regression

From previous studies, it could be observed that the linear regression model may not be the most appropriate for accident prediction on bridges since the statistical distribution of the whole crash data is not of the normal type. However, taking a logarithm function of the accident risk, as shown in Figure 6.21, the distribution now appears to be normal. An appropriate model for such data is the logistic regression. The main problem here is how to deal with those bridges with no accident recorded on them, i.e., accident frequency is 0. A solution is to introduce the binomial logistic regression model. A binary (or binomial) logistic regression is recommended when the dependent variable is a dichotomy (an event happened or not) and can be applied to test the association between a dependent variable and the related potential factors, to rank the relative importance of independent variables, and to assess interaction effects.

Binary logistic regression is used in this study to estimate the probability of accident occurring on the bridge. If there is no accident on the bridge, the new dependent variable should be 0, otherwise is 1, no matter how many accidents happened. The probability that an accident will occur on a specific bridge is modeled as logistic distribution in equation 6.20:

$$\pi(x) = \frac{e^{g(x)}}{1 + e^{g(x)}} \qquad (6.20)$$

The logit of the multiple logistic regression model is given by equation 6.21:

$$g(x) = \ln\left[\frac{\pi(x)}{1 - \pi(x)}\right] = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \cdots + \beta_n x_n \qquad (6.21)$$

where π = conditional probability of a bridge accident;
x_i = independent variables;
β_i = coefficient for each independent variables.

The next step is to prepare significant variables since many variables could relate to bridge accidents. In the previous bridge accident models discussed in this report, we have considered many variables including the functional class, deck rating, and approach alignment. As described earlier, modifications (such as binary form "dummy variables") of these data items had to be computed, to make them suitable for the regression analysis. For instance the variable "funcclass_m" is a new modified functional class, as a zero/one variable depending on the range of possible values of the functional class variable. The same reasoning was applied to the deck rating variable. Now that there are many potential variables for the model, there is a need to select the significant ones.

There are two ways to choose the significant variables: one is using correlation analysis, and the other is using stepwise regression. Correlation analysis is a statistical technique that describes the degrees of the relationship between two variables. Correlation analysis is not a cause-effect analysis among variables in which the effect of one variable over the other is determined. However, knowing the degree of association among independent variables is important as it assists in eliminating the variables that are co-varying.

The STATA software package was utilized, starting with 19 variables related to bridge accidents. As shown in Appendix A Table D1, some pairs of the variables have strong inter-correlation, for example, approach roadway and bridge roadway widths ("aroadwidth" and "roadwidth"); and funnel ratio (the ratio of approach roadway width to the bridge roadway width) and a funnel ratio factor (dummy variable to classify values), i.e., "funnel" and "funnel_m". For such highly inter-correlated variables, only one of the two can be used, choosing the one with highest correlation with the logit dependent variable. Thus, for example "funnel" is chosen because it has the higher correlation coefficient 0.107. Based the highest values of correlation coefficients, the following nine variables were chosen after the correlation analysis: speed; funnel; sumlanes (total number of lanes); narrowness; curbsw (curb and sidewalk width); length; ADT; funcclass_m; and dkrating_m.

6.7.3.2.1 Stepwise regression

Stepwise regression includes regression models in which the choice of predictive variables is carried out by an automatic procedure. Usually, this takes the form of a sequence of F-tests, but other techniques are possible, such as t-tests, adjusted R-square, Akaike information criterion, Bayesian information criterion, Mallows' Cp, or false discovery rate. The main approaches are:

- Forward selection, which involves starting with no variables in the model, trying out the variables one by one and including them if they are 'statistically significant'.

- Backward elimination, which involves starting with all candidate variables and testing them one by one for statistical significance, deleting any that are not significant.

- Methods that are a combination of the above, testing at each stage for variables to be included or excluded.

Again, using STATA software, results of the stepwise regression analysis are shown in Appendix Table D2, indicating that the selected nine variables are significant in terms of bridge accidents. Therefore, these nine variables are the main factors involved in logistic regression model.

6.7.3.2.2 Goodness-of-fit measure

In Ordinary Least Squares regression (OLS) methods, the coefficient of determination (R-square) is accepted as a measure of how well the formulated regression model represents the data. In the case of Poisson-related regression models, the R-square measure is not appropriate. Instead, as suggested by

Adel-Aty and Radwan (2000), Fridstrom et al. (1995), and Agresti (1990), other measures are recommended, including the deviance value, D, and the log-likelihood ratio, ρ^2. Both are defined in terms of a comparison of the log-likelihood of the complete fitted model (with all explanatory variables) to that of the model with only the constant (no explanatory variable). D is a χ^2 test statistic for the test that at least one explanatory variable's regression coefficient is not equal to zero in the model, with the degrees of freedom defined by the number of explanatory variables. The measure ρ^2 is analogous (but not the same as) the R-square used in OLS. Specifically, the goodness-of-fit measures D and ρ^2 are defined as follows:

$$D = 2(LL(\beta) - LL(0))$$

and

$$\rho^2 = 1 - \left(\frac{LL(\beta)}{LL(0)} \right)$$

where

$LL(0)$ = Log-likelihood of the model with only the constant (no explanatory variable)
$LL(\beta)$ = Log-likelihood of the full model (with all explanatory variables)

Also computed for D as a test of significance is the *p-value*, or the probability of obtaining a significant χ^2 test statistic if there is actually no effect of the explanatory variables (Type I error). This p-value is compared to a specified alpha level, which is typically set at 0.05 or 0.01. Small p-values, less than the specified alpha level, would indicate that at least one of the regression coefficients in the model is equal to zero.

Montella et al. (2009) also described the Akaike Information Criteria (AIC) as another suitable goodness-of-fit measure. The AIC value is calculated as follows:

$$AIC = -2LL(\beta) + 2p$$

where

p = Number of parameters in the fitted model

The lower the value of AIC, the better-fitting the model is, with the first term estimating the bias or how bad the model is, and the second term penalizing the model for excessive number of variables.

6.7.3.2.3 Formulating logistic regression model

Using the nine independent predictive variables, and using a dichotomy variable (0 indicates no accident and 1 indicates at least one accident) as the dependent variable, the logistic regression is developed using the STATA software package. First, the LOGISTIC command is used to obtain the "odds ratios" and coefficients. "Odds ratio" here means the probability of the outcome event occurring divided by the probability of the event not occurring. The odds ratio that is equal to exp ($x\beta$) tells the relative amount by which the odds of the outcome increase (or greater than 1.0) or decrease (or less than 1.0) when the value of the predictor variable is increased by 1.0 units (David and Lemeshow, 1989). Because the output is not directly relevant to the estimate of accident probability, the results are shown in Table D3 of Appendix A. On the other hand, the logistic regression model showing the needed information on variable coefficients for estimating the probability of accidents is shown below in Table 6.31.

Table 6.31. Logistic regression analysis output showing coefficients

Independent variable (logit model)	Coefficient	Standard error	z	Prob > |z|
Constant	-3.025499	0.147803	-20.47	0.000
Speed limit on bridge (mph)	0.006514	0.001568	4.16	0.000
Funnel (ratio of approach roadway width to bridge roadway width (ft.))	0.205753	0.106564	1.93	0.054
Total number of lanes	0.178024	0.018414	9.67	0.000
Narrowness (ratio of no. of lanes to bridge roadway width)	2.988808	0.484835	6.16	0.000
Curb sidewalk width (ft.)	0.030899	0.012561	2.46	0.014
Length of bridge (mile)	1.242759	0.103124	12.05	0.000
Average daily traffic (veh/day)	0.000044	0.000001	37.23	0.000
Function class factor (dummy variable, 1 if 11, 14, or 16, 0 otherwise)	0.629291	0.036408	17.28	0.000
Deck rating factor (dummy variable, 1 less than 6, 0 otherwise)	0.468928	0.108347	4.33	0.000
Summary statistics				
Number of crashes	21684			
Log-likelihood at zero, LL(0)	-15030.14			
Log-likelihood at convergence, LL(β)	-11636.20			
Deviance D = 2(LL(β) - LL(0))	6787.89			
pseudo R^2 or $\rho^2 = 1 -$ LL(β)/LL(0)	0.2258			
AIC	23292.40			
Prob > χ^2 (Deviance)	0.0000			

6.7.3.2.4 Discussion of results

Using four years of accident data (2003 to 2006) the logistic model was established, as shown above, as a predictive model for bridge accidents that occurred in 2007. Based on the equations 6.20 and 6.21, the probability that each bridge may have an accident could be predicted as shown in Figures 6.26 and 6.27. The frequency histograms are shown in Figure 6.26 for bridges where crashes are known to occur or not occur in 2007, while the percentages are shown in Figure 6.27. For those 2601 bridges which actually had no accident 2007, it was predicted that about 51% of them have smaller than 0.3 probability of having an accident, while about 80% of them have a probability smaller than 0.5 (Figure 6.27). But the distribution of the 2,820 bridges which actually had accidents in 2007, was not as well predicted; it could be seen that only about 43% of these particular bridges have greater than 0.7 probability of having an accident, and only about 65% have a probability greater than 0.5 (Figure 6.27).

Looking at it in another way, it was observed that there were 1,500 bridges that actually had no accidents every year from 2003 to 2006. The 2007 records showed that 1,310 bridges of those 1,500 bridges actually had no accident in 2007, and only 190 had accidents. The logistic model predicted the occurrence of accidents as shown in Figure 6.28. It could be that about 64% of these 1,500 bridges have accident probability predicted as being smaller than 0.3, and about 87% of them have predicted probability smaller than 0.5 (Figure 6.28). If an acceptable probability criterion is set as 0.3 or 0.5, then the prediction accuracy can be interpreted as 0.64 and 0.87 respectively.

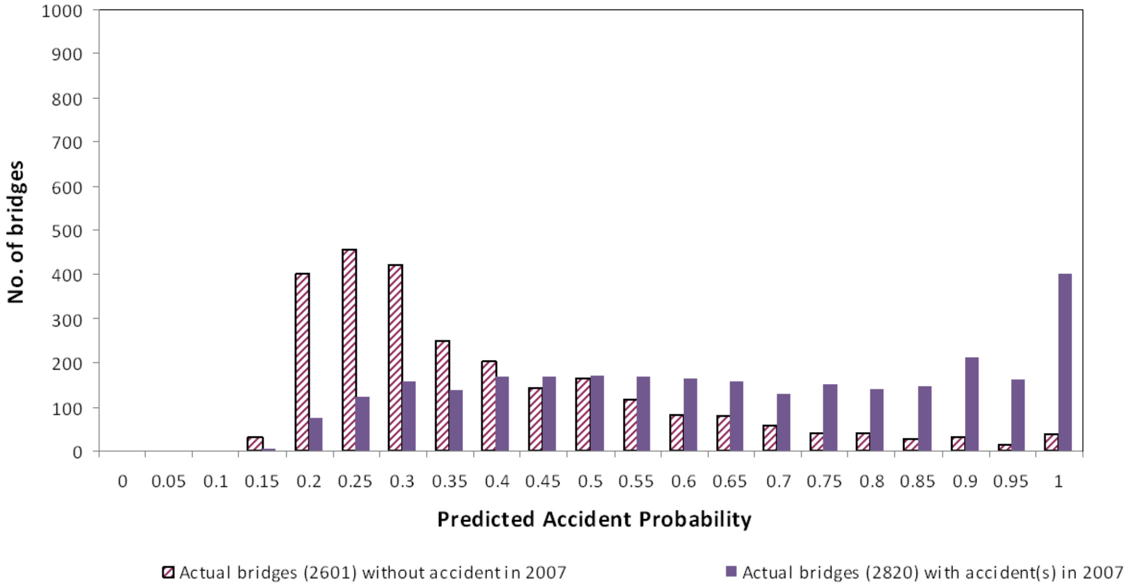


Figure 6.26. Logistic model accident prediction for 2007 on bridges showing frequency

Also, there were 1,603 bridges that actually had accidents every year from 2003 to 2006. Using these data, we could predict the accident probability in 2007 for these bridges and compare them to actual data, as shown in Figure 6.29. Actually, 1,490 bridges of those 1,603 bridges had accidents in 2007, and only 113 had no accident. The logistic model predicted that about 63% of these bridges have greater than 0.7 probability of having crashes, and about 84% of them have probability greater than 0.5. Again, if an acceptable probability criterion is set as 0.7 or 0.5, then the prediction accuracy can be interpreted as 0.63 and 0.84 respectively.

Depending on the threshold probability of classifying the occurrence or non-occurrence of accidents, the prediction of the logistic regression model can be considered reasonable. For the bridges considered in Figures 6.26 and 6.27, the variation in the means of some independent variables in the logistic model relative to the predicted probability of accidents on the bridge, are shown in Table 6.32. Using less than 0.3 probability as a threshold for non-occurrence of accident, it could be seen that fewer lanes on the bridge roadway, shorter bridge length, and lower traffic volume will imply lower probability of accident occurrence on the bridge. On the other hand, using greater than 0.7 probability as a cutoff point for occurrence of accidents on the bridge, it is observed that higher speed, more lanes, longer bridge length, and more traffic volume will increase the chances of accidents occurring on the bridge.

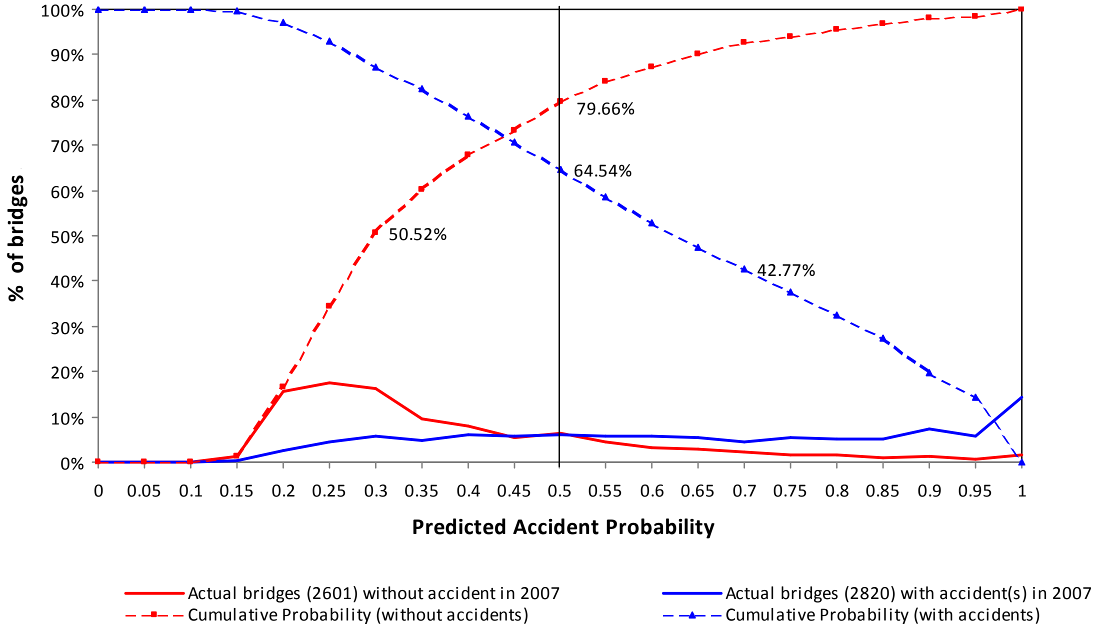


Figure 6.27. Logistic model accident prediction for 2007 on bridges showing percentages

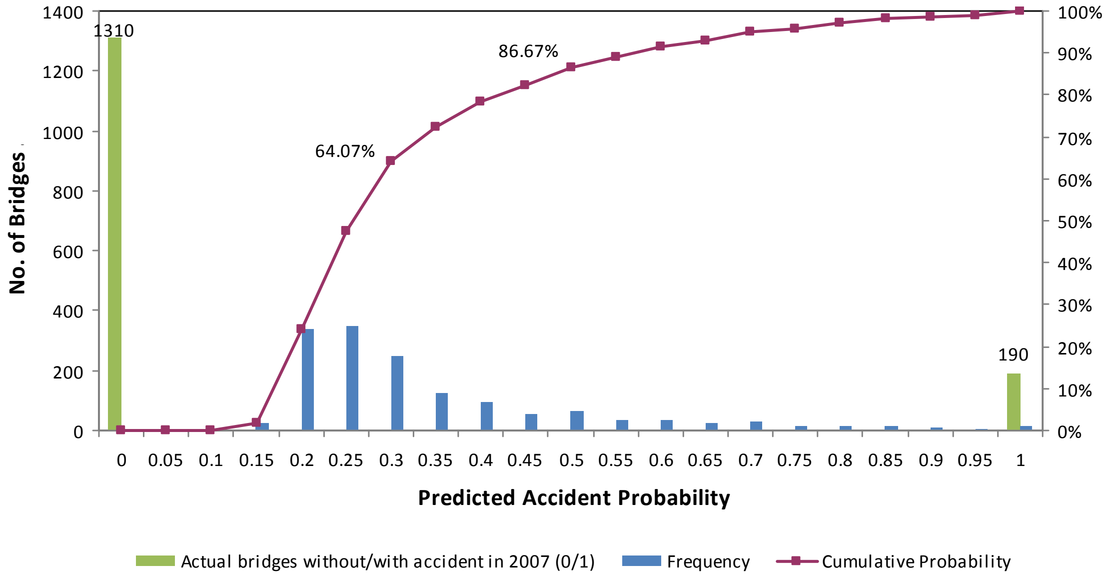


Figure 6.28. Logistic model accident prediction for 2007 on bridges with no accidents each year from 2003 to 2006

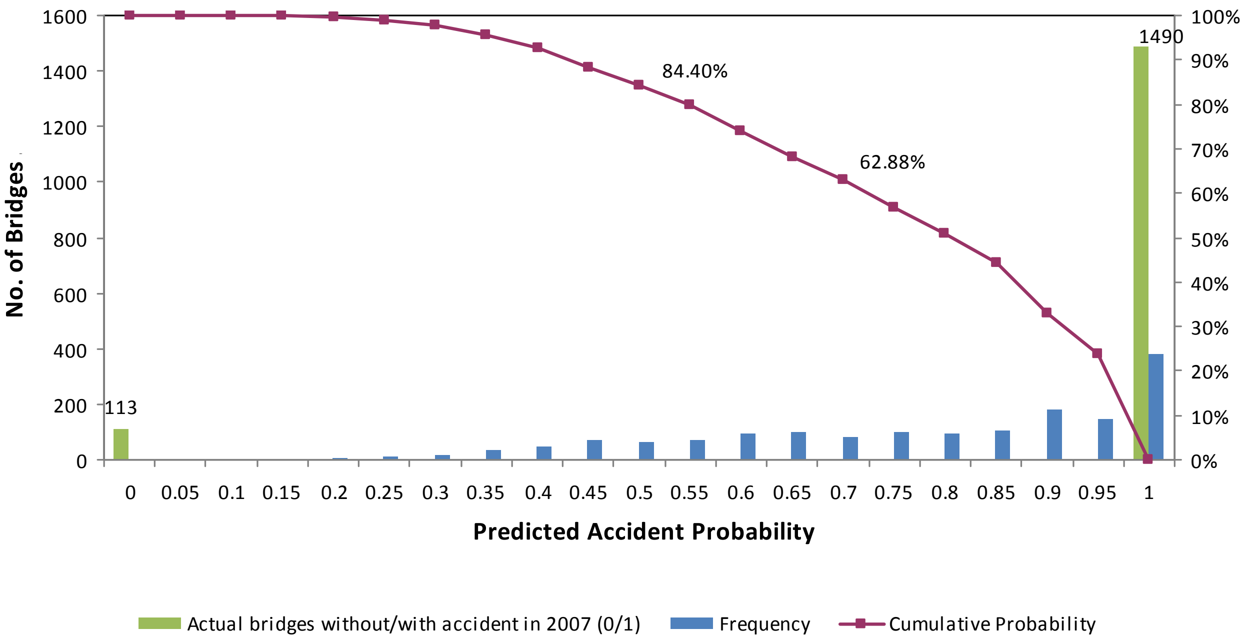


Figure 6.29. Logistic model accident prediction for 2007 on bridges with accidents each year from 2003 to 2006

Table 6.32. Variables differences in logistic regression prediction model

	Probability	Speed	No. of anes	Curbsw	Length	ADT	Funcclass_m
No Accident	<0.3	53.174	1.935	0.243	0.046	5207	0.048
	>0.3	51.121	2.713	0.755	0.105	23788	0.502
Accident	>0.7	56.022	4.725	1.004	0.150	74748	0.764
	<0.7	51.502	2.736	0.779	0.101	23136	0.490

Numbers of accidents per year on highway bridges are count data, in which the observations can take only the non-negative integer values (0, 1, 2, 3 ...), and where these integers arise from counting rather than ranking. Statistical methods such as least squares and analysis of variance are designed to deal with continuous dependent variables. These can be adapted to deal with count data by using data transformations such as the square root transformation, but such methods have several drawbacks; they are approximate at best and estimate parameters that are often hard to interpret. The Poisson, binomial and negative binomial distributions are commonly used to represent the distributions of count data when these are treated as random variables.

The Poisson distribution can form the basis for some analyses of count data and in this case Poisson regression may be used. This is a special case of the class of generalized linear models which also contains specific forms of model capable of using the binomial distribution (such as binomial regression and logistic regression) or the negative binomial distribution where the assumptions of the Poisson model are violated, in particular when the range of count values is limited or when over-dispersion is present.

6.7.3.3 Poisson regression

Poisson regression is a form of regression analysis used to model count data and contingency tables. Poisson regression assumes the response (dependent) variable Y has a Poisson distribution, and assumes the logarithm of its expected value can be modeled by a linear combination of unknown parameters and independent variables. In the simplest case with a single independent variable x, the Poisson probability distribution takes the form:

$$\Pr(Y=y|\lambda)=\frac{e^{-\lambda}\lambda^{y}}{y!} \text{ for } y=0,1,2,\ldots \qquad (6.22)$$

where λ = the mean or expected value, and the variance of a Poisson distribution

The Likelihood function for the Poisson model is

$$L(\beta|y,X)=\prod_{i=1}^{N}\Pr(y_i|\mu_i)=\prod_{i=1}^{N}\frac{e^{(-\mu_i)}\mu_i^{y_i}}{y_i!} \qquad (6.23)$$

$$\text{where } \mu_i=E[y_i|x_i]=e^{(x_i\beta)}$$

A characteristic of the Poisson distribution is that its mean is equal to its variance. In certain circumstances, it will be found that the observed variance is greater than the mean, called over-dispersion, which indicates that the model is not appropriate. A common reason is the omission of relevant explanatory variables.

Another common problem with Poisson regression is excess zeros: if there are two processes at work, one determining whether there are zero events, and a Poisson process determining how many events there are, there will be more zeros than a Poisson regression would predict. In these cases, generalized linear models such as the negative binomial model are preferable.

6.7.3.4 Negative binomial regression

The negative binomial distribution can be used as an alternative to the Poisson distribution. It is especially useful for discrete data over an unbounded positive range whose sample variance exceeds the sample mean. If a Poisson distribution is used to model such data, the model mean and variance are equal. In that case, the observations are over-dispersed with respect to the Poisson model. Since the negative binomial distribution has one more parameter than the Poisson, the second parameter can be used to adjust the variance independently of the mean.

One formulation of the negative binomial distribution can be used to model count data with over-dispersion.

$$\Pr(Y=y|\lambda,\alpha)=\frac{\Gamma(y+\alpha^{-1})}{y!\,\Gamma(\alpha^{-1})}\left(\frac{\alpha^{-1}}{\alpha^{-1}+\lambda}\right)^{\alpha^{-1}}\left(\frac{\lambda}{\alpha^{-1}+\lambda}\right)^{y} \qquad (6.24)$$

where

λ = the mean or expected value of the distribution

α = the over-dispersion parameter

When α =0 the negative binomial distribution is the same as a Poisson distribution.

The Likelihood function for the negative binomial model is

$$L(\beta|y,X) = \prod_{i=1}^{N} \Pr(y_i|x_i) = \prod_{i=1}^{N} \frac{\Gamma(y_i+\alpha^{-1})}{y_i!\,\Gamma(\alpha^{-1})}\left(\frac{\alpha^{-1}}{\alpha^{-1}+\mu_i}\right)^{\alpha^{-1}}\left(\frac{\mu_i}{\alpha^{-1}+\mu_i}\right)^{y_i} \qquad (6.25)$$

$$\text{where } \mu_i = E[y_i|x_i] = e^{(x_i\beta)}$$

The next step involves analysis of the simple variable *frequency*, i.e., the number of accidents during every calendar year, to investigate the influence of the bridge attributes. The histogram plot of this variable is shown in Figure 6.30.

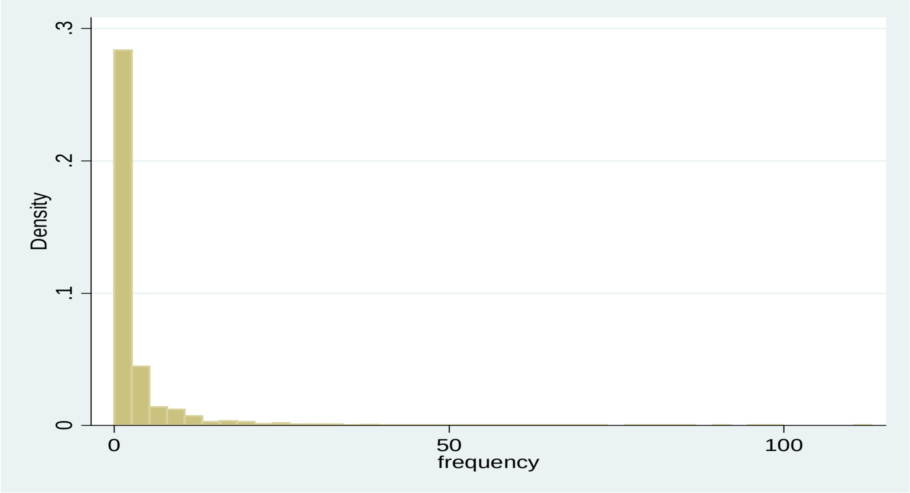


Figure 6.30. Histogram Plot of the annual frequency of accidents

From Figure 6.30 above, we can see the data are strongly skewed to the right; clearly OLS regression would be inappropriate. It is suggested that count data follows a Poisson distribution. However, there is a prerequisite of the Poisson distribution, which is that the mean and variance should be the same. The summary statistics of the frequency of 21684 observed accidents are as follows: Mean = 2.767; Standard deviation = 6.523; Variance = 42.549; and Kurtosis = 53.937. It could be seen that the variance is nearly 15 times larger than the mean, which indicates over-dispersion. Let's run a Poisson regression though we believe this is not a good choice.

We learned from the previous study that six independent variables, including speed, number of lanes (***sumlanes***), curb/sidewalk clearance (***curbsw***), length (***lengthmi***), ADT (***adt2***) and functional classes (***fc_m***), are more responsible for accident frequency than other variables. In the meantime, there are other factors that significantly influence accident frequency other than bridge attributes, such as driver age (***age***) and time of day (***ctime***). We will add those two variables as second model. In a third model, 5 more variables, approach roadway width (***aroadwith***), ***funne***l (ratio of approach roadway width and roadway width), ***relativewidth*** (difference between roadway width and approach roadway width), ***narrowness*** and deck rating (***dkrating***), will be included to test the significance level of variables.

The negative binomial regression model can be formally represented as follows:

$$E(y) = \exp\{\beta_0 + \beta_1 * speed + \beta_2 * sumlanes + \beta_3 * curbsw + \beta_4 * lengthmi + \beta_5 * adt + \beta_6 * fc\_m\} \quad (6.26)$$

where,

$E(y)$ = Expected count of accident

β_i = Regression coefficients, i = 0 for the constant term; and i = 1,2, ..6 for the explanatory variables.
speed = Speed limit on bridge (mph).
sumlanes = Total number of lanes.
curbsw = Curb sidewalk width (ft.)
lengthmi = Length of bridge (mile)
adt = Average daily traffic (veh/day)
fc_m = Function class factor (dummy variable, equals 1 if 11, 14, or 16; equals 0 otherwise)

The output results for the Poisson regression models are also shown in Tables D4 to D6 in Appendix D. Though all three models showed some statistical significance, the large values for chi-square in the goodness-of-fit (gof) test**"** of all three Poisson regressions confirmed that the Poisson distribution was inappropriate for these data.

The results of the three negative binomial models (with the same scenarios as in the Poisson regression models) are presented in Tables 6.34 to 6.36. First it should be noted that the over dispersion parameter (α) in each model is greater than zero, confirming that the negative binomial model is more appropriate than Poisson models for the bridge crash data.

Looking at the results for model 1 in Table 6.33, all the explanatory variables are significant, as indicated by the p-values of the regression coefficients. The length of the bridge, measured in miles, has a strong increasing influence on the number of accidents on abridge. Increase in the number of lanes on the bridge will increase the chances of accidents on the bridge. Similarly, a wider curb/sidewalk on a bridge will suggest more accidents on the bridge. The more vehicles using the bridge, i.e, increase in ADT, the higher the likelihood of accidents. Surprisingly, the regression coefficient for speed is negative, implying that accidents are reduced at higher speed. It should be noted however that the coefficient is very small, making the decrease very negligible; for example, it will take a decrease in speed of about 50 mph to obtain an increase of one accident (based on the partial estimate of e(βx)).

In model 2, as shown in Table 6.34, addition of two more explanatory variables not related to bridge or roadway (driver's age and time of the crash) seems to improve the model as observed in the increase in the pseudo R^2. All the explanatory variables are also statistically significant, as indicated by the p-values of the regression coefficients, and the over dispersion parameter (α) is 0.83. In general, the increasing or decreasing effects of the bridge-related variables are similar to model 1, except that the regression coefficients are different now for some of the variables. It should be noted however that in reality, the variables such as the time of accident and a human factor-related variables such as driver's age cannot be used in a prediction model as desired in this study. Identifying the specific time input for individual bridges is almost impossible, as well as entering specific ages for drivers traveling across the individual bridges.

For model 3, more bridge-related variables are added to model 1, resulting in similar effects of the explanatory variables on the prediction of crashes (Table 6.35). Judging by the p-value on the regression coefficients in Model 3, all variables are statistically significant except for "relative width." Also, for Model 3, the over dispersion parameter (α) is 1.59. But the pseudo R^2 is about the same, so the addition of the variables is not statistically beneficial.

Table 6.33. Negative binomial regression Model 1

Independent variable	Coefficient	Standard error	z	Prob > |z|
Constant	-0.432151	0.065349	-6.61	0.000
Speed limit on bridge (mph)	-0.013269	0.001060	-12.52	0.000
Total number of lanes	0.177415	0.009045	19.62	0.000
Curb sidewalk width (ft.)	0.108291	0.007305	14.83	0.000
Length of bridge (mile)	0.963363	0.051232	18.80	0.000
Average daily traffic (veh/day)	0.000027	0.000001	50.35	0.000
Function class factor (dummy variable, 1 if 11, 14, or 16, 0 otherwise)	0.406270	0.023091	17.59	0.000
Summary statistics				
Number of crashes	21684			
Log-likelihood at zero, LL(0)	-42131.97			
Log-likelihood at convergence, LL(b)	-37427.76			
Deviance D = 2(LL(b) - LL(0))	9408.42			
pseudo R^2 or r^2 = 1 - LL(b)/LL(0)	0.1144			
Prob > c^2 (Deviance)	0.0000			
AIC	74869.52			
Over dispersion parameter (a)	1.631			

Table 6.34. Negative binomial regression Model 2

Independent variable	Coefficient	Standard error	z	Prob > |z|
Constant	-1.824461	0.063893	-28.56	0.000
Speed limit on bridge (mph)	-0.015542	0.000999	-15.56	0.000
Total number of lanes	0.094532	0.007232	13.07	0.000
Curb sidewalk width (ft.)	0.055304	0.006303	8.77	0.000
Length of bridge (mile)	0.645831	0.035906	17.99	0.000
Average daily traffic (veh/day)	0.000018	0.000000	45.74	0.000
Function class factor (dummy variable, 1 if 11, 14, or 16, 0 otherwise)	0.090620	0.020971	4.32	0.000
Driver's age (at fault)	0.031878	0.000819	38.91	0.000
Time of crash	3.414460	0.054590	62.55	0.000
Summary statistics				
Number of crashes	21684			
Log-likelihood at zero, LL(0)	-42131.98			
Log-likelihood at convergence, LL(b)	-31031.71			
Deviance D = 2(LL(b) - LL(0))	22200.53			
pseudo R^2 or r^2 = 1 - LL(b)/LL(0)	0.2635			
Prob > c^2 (Deviance)	0.0000			
AIC	62081.422			
Over dispersion parameter (a)	0.830			

Table 6.35. Negative binomial regression Model 3

Independent variable	Coefficient	Standard error	z	Prob > |z|
Constant	-1.564787	0.206204	-7.59	0.000
Speed limit on bridge (mph)	-0.011122	0.001060	-10.50	0.000
Approach roadway width (ft.)	0.012685	0.007515	1.69	0.091
Funnel (ratio of approach roadway width to bridge roadway width (ft.))	0.460018	0.176175	2.61	0.009
Relative width (approach roadway width minus bridge roadway width (ft.))	0.004008	0.011569	0.35	0.729
Total number of lanes	0.089750	0.039058	2.30	0.022
Narrowness (ratio of no. of lanes to bridge roadway width)	3.546905	0.657943	5.39	0.000
Curb sidewalk width (ft.)	0.096693	0.007301	13.24	0.000
Length of bridge (mile)	0.936793	0.051435	18.21	0.000
Average daily traffic (veh/day)	0.000025	0.000001	48.32	0.000
Function class factor (dummy variable, 1 if 11, 14, or 16, 0 otherwise)	0.397773	0.023080	17.23	0.000
Deck rating factor (dummy variable, 1 less than 6, 0 otherwise)	0.129092	0.062464	2.07	0.039
Summary statistics				
Number of crashes	21684			
Log-likelihood at zero, LL(0)	-42131.98			
Log-likelihood at convergence, LL(b)	-37311.29			
Deviance D = 2(LL(b) - LL(0))	9641.37			
pseudo R^2 or r^2 = 1 - LL(b)/LL(0)	0.1144			
Prob > c^2 (Deviance)	0.0000			
AIC	74646.58			
Over dispersion parameter (a)	1.591			

Though not shown in the output table for each of the three models, the likelihood ratio tests reject the hypotheses that α=0, which again confirmed that negative binomial regression is preferable to Poisson regression. A frequency plot shown in Figure 6.31, compares, using the same accident data, the observation proportions from Poisson and negative binomial distributions. Of all three models, the second model seems preferable. However, in the real world, driver's age and crash time of day are not bridge attributes. They are therefore not necessary for a predictive model based on bridge characteristics. For similar reasons, alcohol/drug use, vehicle characteristics, and other important variables have been excluded from the model.

Applying model 1 on the accident data from 2003 to 2006, the accidents for 2007 were predicted and compared to the actual (observed) accident counts. Figure 6.32 shows the comparison in terms of the bridge inventory distribution of accident counts. In 2007, no accidents were observed on 2601 bridges or about 48% of the 5421 Florida bridges observed, while about 90% of the bridges had accident counts less than 7. Model 1 predicts that only about 10% bridges will have no accidents in 2007 but that 89% bridges would have accidents less than 7. Model 1 also predicts that about 52% of the bridges will have one accident, compared to the roughly 17% of bridges observed to have had one accident in 2007. But for the larger counts of accidents, the correlation between predicted and actual counts appears to be better. With focus on a specific count of accident, for example looking at bridges in 2007 with actually one accident, the distribution of prediction errors at such a specific count is as shown in Figure 6.33.

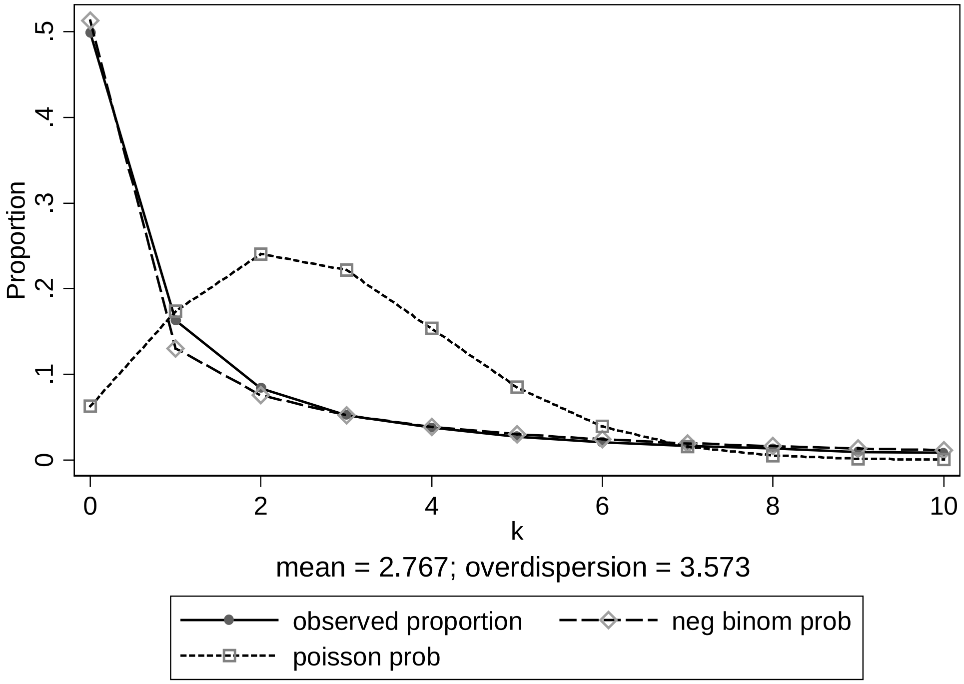


Figure 6.31. Distribution of Poisson and Negative binomial regression

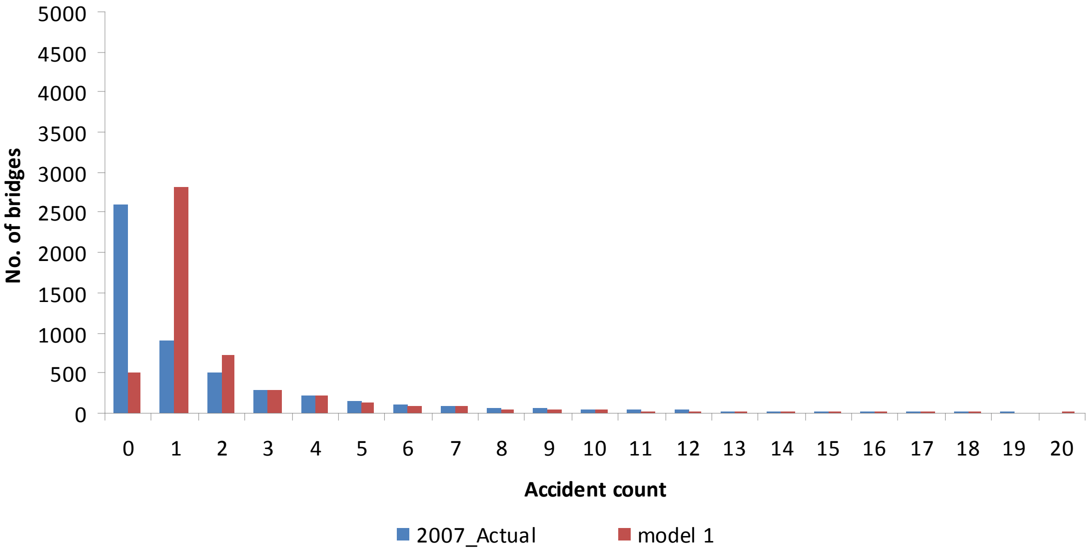


Figure 6.32. Bridge Inventory comparison of prediction and observation for 2007 accidents

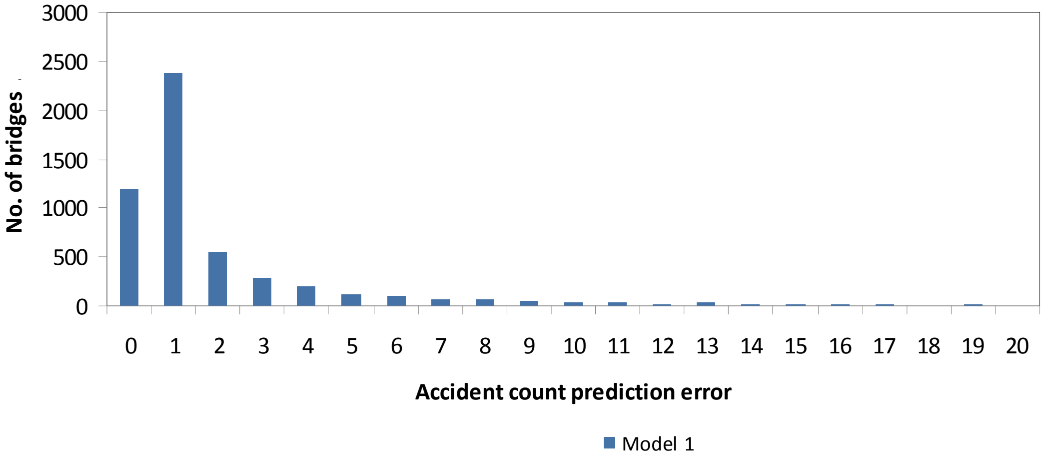


Figure 6.33. Accident prediction errors for Model 1

6.7.4 Discussion

Various models were developed in this study to aid in the prediction of annual frequency of accidents on Florida bridges. Starting with the existing linear regression model, originally developed by Thompson (1999), new coefficients were determined using four years of accident data. Poisson, logistic, and negative binomial regression models were also formulated with accident data. As discussed in the report, both the linear model and the negative binomial models can be reasonably used to predict bridge accidents. A comparison was conducted on the prediction accuracy of these two models. At each specific count of accidents observed in the 2007 accident data, the prediction error of each model was computed as the absolute difference between this actual count and the number of accidents predicted by the model. For example, looking at all bridges with two accidents recorded (actual) for them in 2007, the model is used to predict the number of accidents on these same bridges for 2007. The difference in the two results is used to calculate the prediction error for “two-accident count.” The results, limited to observed accident counts of 5 or less, are summarized in Tables 6.37 and 6.38, and also illustrated in Figure 6.34.

In Table 6.36, it is indicated that there were 2601 bridges with no accidents in 2007. The negative binomial model correctly predicted that about 17% of these bridges had no accident and was off by one count on 66% of them. On the same set of bridges, with zero accidents, the linear model predicts that about 32% of them had no accident and was off by one count on about 21%. Similar comparison results are shown for the other specific observed counts of accidents. The negative binomial model appears to be better in accuracy, especially for predictions within an error of one count of accident, performing at above 80% accuracy for observed counts three or less. On the other hand, for the same range of observed accident counts, the linear model performed at between 48% and 66% accuracy for prediction error within one accident count.

Table 6.36. Accident prediction accuracy of linear regression model

	% of total at observed 2007 count					
Prediction Error	0	1	2	3	4	5
0	32.30	19.25	17.42	11.23	6.06	3.95
1	20.57	46.35	30.53	23.51	19.91	6.58
2	15.26	10.84	31.51	22.46	15.15	13.16
3	9.53	7.52	6.46	25.96	23.38	21.05
4	5.84	4.98	3.13	5.26	25.97	28.29
5	5.27	3.43	2.15	2.11	3.46	23.68
6	2.77	0.77	1.37	1.40	0.43	0.00
7	2.15	1.44	0.78	1.05	1.73	0.00
8	1.08	1.66	1.37	1.40	0.87	0.66
9	0.96	0.77	1.17	1.05	0.43	0.00
10	0.65	1.00	1.17	0.70	0.43	0.00
More	3.61	1.99	2.94	3.86	2.16	2.63
Total at observed count	2601	904	511	285	231	152
error <= 1	52.9	65.6	47.9	34.7	26.0	10.5
error > 1	47.1	34.4	52.1	65.3	74.0	89.5

Table 6.37. Accident prediction accuracy of negative binomial regression model

	% of total at observed 2007 count					
Prediction Error	0	1	2	3	4	5
0	16.61	60.62	24.27	11.58	6.06	7.89
1	66.21	23.89	55.77	26.67	15.58	11.18
2	8.65	5.09	6.07	45.26	28.57	11.18
3	2.38	2.54	3.91	4.91	33.33	26.32
4	1.96	2.32	1.57	2.11	1.30	28.29
5	0.92	0.55	0.98	0.35	2.16	1.32
6	0.73	0.77	1.37	0.70	0.87	2.63
7	0.38	0.66	0.78	0.35	0.87	3.29
8	0.35	0.66	0.39	1.40	0.87	0.00
9	0.38	0.66	0.59	0.00	0.43	0.66
10	0.19	0.11	0.39	0.70	2.16	0.66
More	1.23	2.10	3.91	5.96	7.79	6.58
Total at observed count	2601	904	511	285	231	152
error <= 1	82.8	84.5	80.0	38.2	21.6	19.1
error > 1	17.2	15.5	20.0	61.8	78.4	80.9

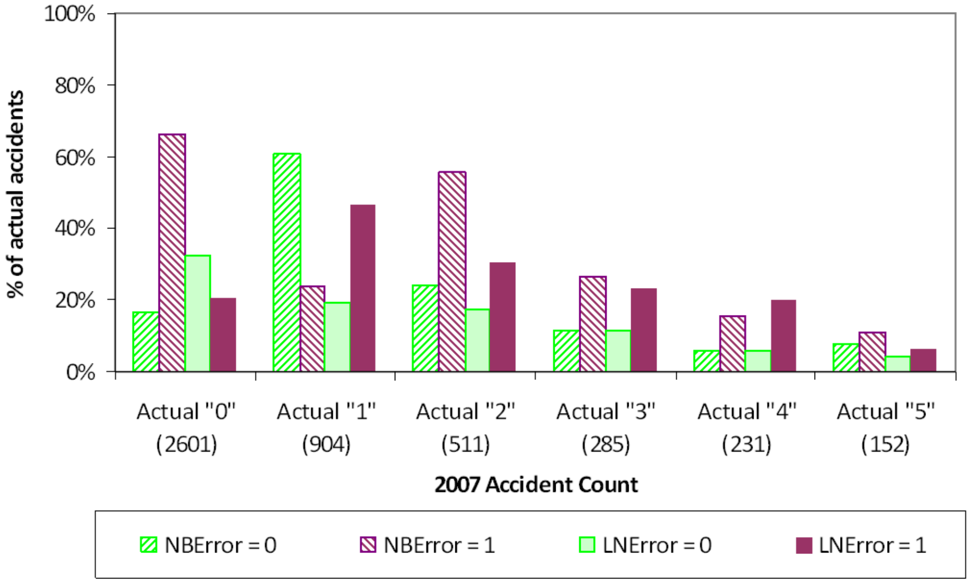


Figure 6.34. Accident prediction accuracy of negative binomial (NB) and linear (LN) regression models

7. Final Implementation

Delivered separately from this final report are these additional items:

- Revised Project Level Analysis Tool (PLAT), an Excel file.
- Revised Network Analysis Tool (NAT), an Excel file.
- PLAT Results File, a Microsoft Access database.
- Revised PLAT Users Manual, delivered in Microsoft Word and Acrobat formats.
- Revised NAT Users Manual, delivered in Microsoft Word and Acrobat formats.
- A Powerpoint file used in the PLAT/NAT training class.
- An Excel file containing database update scripts to facilitate the updating of FDOT’s main Pontis database with the quantitative results of this study.

7.1 Final Database Preparation

After completion of the development of deterioration and cost models, the results of the analysis were applied to a 2008 copy of the Florida Pontis database. For the deterioration model, the results reported above at the element type level were expanded to represent every element and condition state in the database. Median years were converted to transition probabilities. Action effectiveness models and cost models were expanded from the action sub-category level to the element/state/action level. All of these results were then applied to the database using a series of SQL UPDATE statements.

Further processing of the results was conducted using the Pontis 4.4 network optimization procedure (Cambridge 2003) and the 2002 Florida failure cost analysis (Thompson 2003). The failure cost analysis estimates the agency and user costs of failure of each type of element, based on characteristics of the bridge inventory and a set of failure scenarios. As an example of a failure scenario, if a bridge girder fails (does not satisfy required load capacity requirements), then agency and user costs are computed for replacing the girder and detouring all trucks for the period of time necessary for the repair to be completed.

Pontis relies on the failure cost to ensure that the network optimization model programs at least sufficient preservation work to keep bridges in service. The failure cost spreadsheet model computes the minimum failure cost necessary to achieve this result, and increases the failure cost to reflect the agency and user costs of each failure scenario.

The spreadsheet model delivered with the 2003 analysis was updated using the current discount rate of 0.9525. Unit user costs required for this model were obtained from the 1999 Florida Pontis User Cost Study (Thompson et al 1999), and updated using the Consumer Price Index (DOL, 2010). The inflation adjustment of 218/166.6=1.3085 was computed to update 1999 prices to 2010 prices. The following unit user costs resulted:

Vehicle operating costs per km	$ 0.35
Travel time costs per hour	$ 34.58
Accident costs per crash	$123,382

An average bridge replacement cost of $1066 per square meter was used, based on the analysis presented earlier in this report. Other parameters required for the failure cost model were kept the same as in the 2003 analysis.

The failure cost analysis is an iterative procedure that investigates several potential values of the failure cost for each element, executing the Pontis network optimization between iterations. The procedure ensures that valid results are obtained for all elements. The final results inserted into the database include agency and user costs of element failure; the network optimal choice of action for each element and condition state; and the long-term cost of each element, state, and action, which is used in preservation benefit computations.

The completed deterioration and cost models, including failure costs, are a major deliverable of the study. A set of SQL update statements was prepared in an Excel file, to facilitate the quick insertion of the results into the Department's production Pontis database by FDOT staff.

7.2 Software Enhancements and Training

The updated data were also used in the development, testing, and demonstration of enhancements to the Project Level Analysis Tool (PLAT). The following enhancements were completed:

- Incorporation of the new NBI Translator in the PLAT. The new translator provided an improved forecast of future NBI condition ratings. This work also included removing the software that had previously been used to interface to the FHWA NBI Translator.
- Modification of the deterioration model to implement the new Weibull model of the onset of deterioration. This employs the equations presented earlier in this report to forecast the fraction of an element in condition state 1 as a function of age; and the ability to compute an equivalent age from a given fraction in condition state 1.
- Addition of a switch to turn off the user cost computation if desired by the user. This has the same effect as setting the user cost weight to zero. This enables modeling and prioritization based purely on agency costs.
- A minor change to PLAT to present the most recent element-level inspection notes as spreadsheet cell comments in the PLAT dashboard.
- Minor behind-the-scenes repairs and usability improvements to the PLAT and NAT software, including minor changes to ensure compatibility with Excel 2007 and Windows 7.
- Updates to the PLAT and NAT Users Manuals to reflect these changes in the software.

The revised software was used in a training class presented on August 10, 2010. The slides from the class were provided to the Department as a separate deliverable.

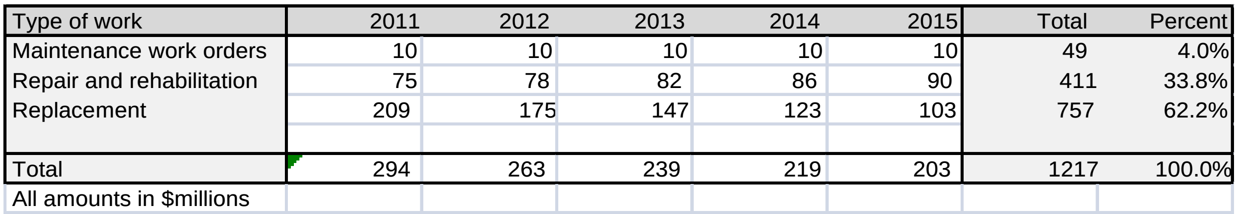
7.3 Investment Decision Rules

Using the revised PLAT and NAT software, a summary analysis was performed to look for general conclusions that might be drawn from the models, particularly regarding the program size and allocation among types of work; and the effect of the new deterioration model on the types of work recommended. The analysis was performed using the 2008 Pontis database, for the 6,528 state-maintained bridges (excluding non-bridge structures) in the database.

It should be noted that this analysis does not take into account work that has already been performed on the bridges since 2008, even though it does account for predicted deterioration during that time. It is not meant to be a needs study, but merely a reasonableness check on the software, and a demonstration of some of the uses to which the software might be put.

For the purposes of this analysis, a five-year test period was assumed, with the funding levels in Figure 7.1.

Figure 7.1. Funding levels used in the analysis



Type of work	2011	2012	2013	2014	2015	Total	Percent
Maintenance work orders	10	10	10	10	10	49	4.0%
Repair and rehabilitation	75	78	82	86	90	411	33.8%
Replacement	209	175	147	123	103	757	62.2%
Total	294	263	239	219	203	1217	100.0%
All amounts in $millions							

These funding levels were determined in consultation with FDOT staff. The funding levels include all bridge work under maintenance work orders and contracts, for all types of work up to and including bridge replacement. Included are certain types of work that are not currently modeled in PLAT and NAT:

- Bridges replaced or widened for reasons other than condition or safety-related deficiencies; for example, bridges included in roadway widening projects that add lanes.
- Work that is performed in response to risk factors, such as scour and fatigue mitigation.
- Emergency work necessitated by problems not modeled in the analysis, such as remediation of segmental bridge corrosion issues, shoring of bridges, and repair of collision damage.
- Work whose benefit is enhanced by economies of scale, due to the presence of nearby bridge work (thus saving costs of mobilization and maintenance of traffic). The most prominent examples are paint crew activities and bridge deck repairs.

Future Pontis implementation work is envisioned to correct for some of these omissions. For example, a research study has recently begun, to identify risk factors and to properly represent their role in project identification and priority-setting in the PLAT and NAT systems. Pontis 5.2 will have functionality to model economies of scale in projects involving multiple bridges, and to develop economic data on the impacts of adding lanes to bridges to increase traffic capacity.

PLAT has several configuration parameters that govern the quantity of needs generated and passed along to NAT for the programming analysis. The most significant one was the minimum benefit/cost ratio. In theory this parameter would be set at zero to include all projects whose benefits exceed their costs, where the life cycle cost of the do-nothing candidate is greater than the life cycle cost of the project being evaluated. However, as noted in a number of recent research efforts (Patidar et al, 2007), life cycle costs make up only one part of the total benefit of bridge projects. In particular, risk, mobility, and public attitudes toward deteriorated infrastructure, also play a practical role in how projects are identified and selected. PLAT does not yet have methods to estimate these benefits.

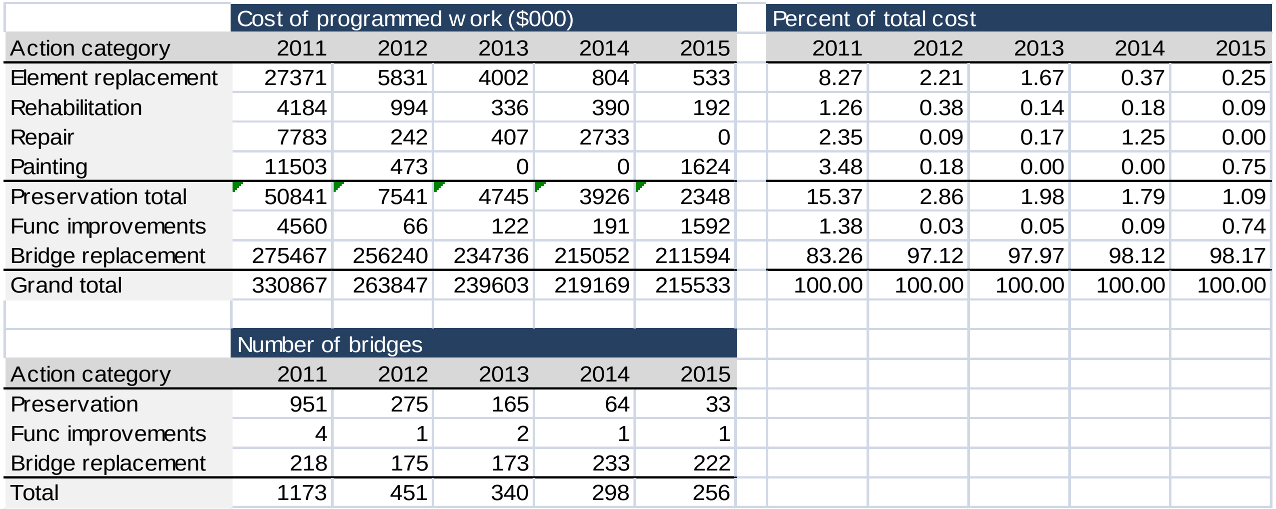
Because of these considerations, the PLAT models at a minimum B/C ratio of 0.0 did not generate enough bridge needs to use up the available funding. The analysis in years 4 and 5 funded all identified projects, and minimized life cycle cost; but these projects were not sufficient to maintain an acceptably high health index. This is likely due to the fact that the life cycle cost model is accounting for only a portion of the benefits.

In the absence of models to more accurately account for these additional benefits, the minimum B/C was reduced, to save more of the PLAT-generated investment alternatives for use in the NAT model. It was found that a minimum B/C ratio of -1.0 provided more than enough alternatives. Because of the application of budget constraints, only a small fraction of the alternatives with B/C below zero were programmed by the NAT model.

Figure 7.2 shows the total costs programmed by the model each year, by action category. It is in this table that the role of missing benefits is especially apparent. The 2011 distribution of actions is most consistent with historical agency experience. In the later years, the dearth of preservation actions is likely due to lower benefit/cost ratios, caused by lack of a benefit model for conditions and risk. Future research should be able to correct for this, by incorporating multi-objective benefits.

Figure 7.2 was computed with 100% weight given to user costs in the functional improvement model. Even though the user cost component is quite high on individual bridges, it can be seen in the results that functional improvements still make up only a small fraction of overall work programmed.

Figure 7.2. Summary of NAT results



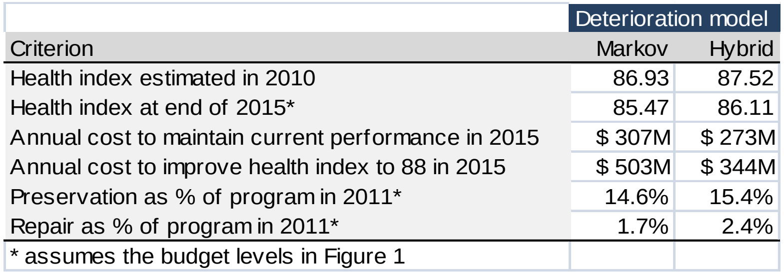
	Cost of programmed w ork ($000)					Percent of total cost				
Action category	2011	2012	2013	2014	2015	2011	2012	2013	2014	2015
Element replacement	27371	5831	4002	804	533	8.27	2.21	1.67	0.37	0.25
Rehabilitation	4184	994	336	390	192	1.26	0.38	0.14	0.18	0.09
Repair	7783	242	407	2733	0	2.35	0.09	0.17	1.25	0.00
Painting	11503	473	0	0	1624	3.48	0.18	0.00	0.00	0.75
Preservation total	50841	7541	4745	3926	2348	15.37	2.86	1.98	1.79	1.09
Func improvements	4560	66	122	191	1592	1.38	0.03	0.05	0.09	0.74
Bridge replacement	275467	256240	234736	215052	211594	83.26	97.12	97.97	98.12	98.17
Grand total	330867	263847	239603	219169	215533	100.00	100.00	100.00	100.00	100.00

	Number of bridges				
Action category	2011	2012	2013	2014	2015
Preservation	951	275	165	64	33
Func improvements	4	1	2	1	1
Bridge replacement	218	175	173	233	222
Total	1173	451	340	298	256

A set of PLAT and NAT models was prepared using the newly developed Markov transition probabilities, but without the Weibull model of the onset of deterioration. This was then compared with the results of the hybrid Weibull/Markov model. This was done to see if the change would make a significant difference at the network level in the allocation of funding. Figure 7.3 shows that the difference is indeed significant.

The PLAT model simulates deterioration from the most recent inspection to the start of the program period, so the two models differ in their initial condition estimates in 2010. This difference continues during the analysis period, so in 2015 the new hybrid model forecasts a significantly higher health index. In order to finish 2015 with the same health index as in 2010, the hybrid model requires significantly less funding each year. In order to finish 2015 at an improved health index of 88, the difference in funding requirements is even greater.

Figure 7.3. Effect of adding the Weibull deterioration model



	Deterioration model	
Criterion	Markov	Hybrid
Health index estimated in 2010	86.93	87.52
Health index at end of 2015*	85.47	86.11
Annual cost to maintain current performance in 2015	$ 307M	$ 273M
Annual cost to improve health index to 88 in 2015	$ 503M	$ 344M
Preservation as % of program in 2011*	14.6%	15.4%
Repair as % of program in 2011*	1.7%	2.4%
* assumes the budget levels in Figure 1		

Figure 7.3 shows that the hybrid model recommends significantly more preservation work. This is likely because the Weibull model causes the effects of preservation actions to last longer. Most of the increase in preservation work occurred in the category of repair actions.

7.4 Next Steps

None of the work presented here on investment decision rules can yet be considered to be a recommendation, primarily because the need for improvement in the benefit model is so clear. It is likely that priorities expressed by the models will change once a multi-objective analysis is introduced. The recently-initiated study to develop risk models will be an important enhancement.

In the meantime, the improved PLAT/NAT model would benefit from a review by FDOT staff of the reasonableness of the results so far, especially at the project level. The multi-objective aspect introduced by the risk models offers great potential for adjusting the relative sensitivity of the models to various policy goals, and also provides opportunities for improvement of important sub-models such as indirect cost and scale feasibility.

One way to approach such a review is to use NAT to identify the specific bridges that are programmed, then use PLAT to view the cost and benefit derivation. Comparing this information with the engineer's actual experience with the bridge, will help to identify ways that the computations of scope, cost, and benefit may be improved.

APPENDIX A. References

AAA, “Your Driving Costs.” American Automobile Association and Runzheimer International, ww2.aaa.com, and www.runzheimer.com, Accessed Dec. 2005.

AASHTO, *AASHTO Guide for Commonly-Recognized (CoRe) Structural Elements*, Interim revision to the 1997 document, American Association of State Highway and Transportation Officials, Washington, DC., 2007.

AASHTO, “User Benefits Analysis for Highways,” American Association of State Highway and Transportation Officials, Washington, DC., 2003.

Abed-Al-Rahim, I., and Johnston D.W., “Estimating bridge-related traffic accident rates and costs,” Transportation Research Record 1392, Transportation Research Board, Washington DC, 1993.

Abdel-Aty, Mohammed A., and Radwan, Essam A., “Modeling traffic accident occurrence and involvement,” Accident Analysis and Prevention 32, 633 – 642, 2000.

Agrawal, A.K & Kawaguchi, A. *Bridge Element Deterioration Rates: Final Report*. Prepared by the City College of New York for the New York State Department of Transportation, Project #C-01-51, 2009.

Agresti, A. Categorical Data Analysis. Wiley, New York, 1990.

Ahlin K., and Granlund, N.O. J. “Relating Road Roughness and Vehicle speeds to Human Whole Body Vibration and Exposure Limits,” International Journal of Pavement Engineering, 2002.

Aldemir-Bektas, Basak and Smadi, Omar G, “A Discussion on the Efficiency of NBI Translator Algorithm,” Transportation Research E-Circular , Issue Number: E-C128, Transportation Research Board, Proceedings, International Bridge and Structure Management: Tenth International Conference on Bridge and Structure Management, October 20-22, 2008, Buffalo, New York, pp 324-335.

Al-Ghamdi, A. “Using logistic regression to estimate the influence of accident factors on accident severity,” Accident Analysis and Prevention, 34, 2002, pp 729-741.

Al-Wazeer, Adel, Nutakor, Chris, and Harris, Bobby, “Comparison of Neural Networks Method versus NBI Translator,” Proceedings CD-ROM, Annual Transportation Research Board (TRB) Meeting, 2007.

FDOT, Annual Reports: Florida Traffic Crash Statistics Report, Florida Department of Transportation (FDOT), 2007.

Archondo-Callao, Rodrigo S. Unpaved Roads’ Roughness Estimation by Subjective Evaluation, Transport No. RT-2, Water and Urban Development, Infrastructure Notes, a Publication of the World Bank, October 1999. Accessed 7/27/2010 from website http://siteresources.worldbank.org/INTRURALM/Resources/514903-1159879214291/td-rt2.pdf

Barnes, G., and Langworthy, P. “Per-mile costs of Operating Automobiles and Trucks.” J. Trans. Res., No.1864, 2004, 71-77.

Blundell, F., “Improvement Optimization Model.” Posted in the on-line Pontis Technical Notes, May 1997.

Brinkman, C.P. and Mak, K. K. “Accident Analysis of Highway Narrow Bridge Sites,” Public Roads 49:4, March 1986, 127-133.

Cambridge Systematics, Inc. *Pontis Release 4 Technical Manual,* Prepared for the American Association of State Highway and Transportation Officials, 2001.

Cambridge Systematics, Inc. *Pontis Release 4.3 Technical Manual*. Washington: American Association of State Highway and Transportation Officials (AASHTO), 2003.

ECONorthwest and Parsons Brinckerhoff Quade & Douglas Inc. “TCRP Report 78:Estimating the Benefits and Costs of Public Transit Projects: A Guidebook for Practitioners.” Transit Cooperative Research Program, 2002.

DOL. Consumer Price Index. US Department of Labor Bureau of Labor Statistics, available at ftp://ftp.bls.gov/pub/special.requests/cpi/cpiai.txt , 2010.

FDOT, “Advisory Inflation Factors for Previous Years (1987 – 2009),” Florida Department of Transportation, Transportation Cost Reports, Office of Policy Planning, Accessed from URL www.dot.state.fl.us/planning/policy/costs on August 13, 2009.

FHWA, *Highway Economic Requirements System Technical Manual*, Federal Highway Administration, U.S. Department of Transportation, Washington DC., 2002.

FHWA, “Recording and Coding Guide for the Structure Inventory and Appraisal of the Nations Bridges,” Report No. FHWA-PD-96-001, Federal Highway Administration (FHWA), Office of Engineering, Bridge Division, December 2005.

Fridstrom, L., Ifver, J., Ingebrigtsen, S., Kulmala, R., and Thomsen, L., “Measuring the contribution of randomness, exposure, weather, and daylight to the variation in road accident counts,” Accident Analysis and Prevention 27 (1), 1995, 1–20.

Forkenbrock, D. J., and Foster, N. S. J. “Accident cost saving and highway attributes,” Transportation, 24, 1997, 79-100.

Frokenbrock, D. J., and Weisbrod, G. E. “Guidebook for Assessing the Social and Economic Effects of Transportation Projects.” NCHRP, Rep.456, National Research Council, Washington DC., 2001.

Golabi, K., Thompson, P. D., and Hyman, W. A. *Pontis Technical Manual*, US Federal Highway Administration, 1992.

Hearn, G., Cavallin J., and Frangopol D. M., “Generation of NBI Condition Ratings from Condition Reports for Commonly Recognized (CoRe) Elements,” University of Colorado at Boulder, Colorado, Final Report submitted to Colorado Department of Transportation, 1997.

Hepburn, S. “A simple model for estimating vehicle operating costs in urban areas,” Road &Transport Research, 3: 2 (June), 1994, 112-118.

Hilbe, J. M. *Negative binomial regression*, Wiley, New York, 2007.

Hine, J., Ellis, S., and Done, S.“Ghana Feeder Road Prioritisation,” Accessed from www.transport-links.org/transport_links/.../1_789_pa3835.pdf , 2000.

Hosmer, D.W., and Lemeshow, S. *Applied logistic regression*, Wiley, New York, 1989.

Johnson, M. “New Caltrans Data on Accident Costs.” posted in the on-line Pontis User Forum, May, 1997.

Johnston, D.W., Chen, C., and Abed-Al-Rahim, I. “Developing User Costs for Bridge Management Systems.” Transportation Research Circular, Vol. 423, 1993, 139-149.

Jung, J., Kaloush, K. E., and Way, G. B. “Life Cycle Cost Analysis: Conventional Versus Asphalt-Rubber Pavements.” Rubber Pavement Association, Tempe, Arizona, 2002.

Martinelli, D. R., and Su, D. “Delay Estimation and Optimal Length for Four-Lane Divided Freeway Work-zones.” J. Trans. Eng., March/April, 1996, 114-122.

Milton, J., and Mannering, F. “The relationship among highway geometrics, traffic-related elements and motor-vehicle accident frequencies.” Transportation 25, 1998, 395-413.

Montella Alfonso, Colantuoni, and Lamberti Renato, “Crash Prediction Models for Rural Motorways,” TRR 2083, 2009, pp1`80-189.

Najafi, F. T., and Soares, R. “User costs at the work zone.” Can. J. Civ. Eng., 28, 2001747-751.

Ossenbruggen P. J., Pendharkar, J., and Ivan, J. “Roadway safety in rural and small urbanized areas.” Accident Analysis and Prevention, 33, 2001, 485-498.

Paterson, W.D.O. and T. Watanatada “Relationships Between Vehicle Speed, Ride Quality, and Road Roughness” in Measuring Road Roughness and Its Effects on User Cost and Comfort. ASTM Special Technical Publication (STP) 884, T.D. Gillespie and M. Sayer, Eds. American Society for Testing and Materials, Philadelphia, 1985, pp. 89-110.

Patidar, Vandana., Samuel Labi, Kumares Sinha, and Paul D. Thompson. *Multi-objective Optimization for Bridge Management Systems.* National Cooperative Highway Research Program Report 590. Washington: Transportation Research Board of the National Academies, 2007.

Shepard, R.W. & Johnson, M.B. California Bridge Health Index: A Diagnostic Tool to Maximize Bridge Longevity, Investment. *TR News* 215, 2001, available online at http://onlinepubs.trb.org/Onlinepubs/trnews/trnews215full.pdf.

Sinha, K., and Labi, S. Transportation Decision Making, Wiley, New York, 2007.

Sobanjo, John O., and Thompson Paul D.. “Development of Agency Maintenance, Repair, and Rehabilitation (MR&R) Cost Data for Florida's Bridge Management System.” Technical Report, Florida Department of Transportation, 2001.

Sobanjo, John, and Thompson Paul D., Project “Planning Models for Florida’s Bridge Management System,” Technical Report, Florida Department of Transportation, 2004.

Sobanjo, John, and Thompson Paul D., “Decision Support for Programming and Budgeting,” Technical Report, Florida Department of Transportation, 2007.

Sobanjo, John O., Thompson, Paul, and Kerr, Richard, “Element-to-Component Translation of Bridge Condition Data,” Proceedings CD-ROM, Annual Transportation Research Board (TRB) Meeting, January 2008, Paper No. 08-3149.

STATA, Analyzing count data, http://www.ats.ucla.edu/stat/Stata/library/count.htm

Thompson, Paul D., Fazil T. Najafi, Roberto Soares, and Hong Jae Choung. *Florida DOT Pontis User Cost Study*. Prepared for the Florida Department of Transportation and available at http://www.pdth.com/images/fdotuser.pdf , 1999.

Thompson, Paul D. *Failure Cost Analysis for Pontis*. Technical Memorandum prepared for the Florida Department of Transportation and available at http://www.pdth.com/images/failcost.zip , 2003.

Thompson, P.D. & Johnson, M.B. Markovian bridge deterioration: developing models from historical data. *Structure and Infrastructure Engineering* 1(1): 2005, 85-91.

Thompson, P.D., Ellis, R.M. & Hong, K. Updating bridge deterioration models with irregular inspection intervals. *In Proceedings of IABMAS 2010: The Fifth International Conference on Bridge Maintenance, Safety and Management*. Rotterdam: Balkema, 2010.

Thompson, P. D., Najafi, F. T., Soares, R., and Choung, H. J. “Florida DOT Pontis User Cost Study,” Technical Report, Florida Department of Transportation, 1999.

Turner, D. S. “Prediction of Bridge accident rates.” ASCE Journal of Transportation Engineering, 110: 1, 1984, 45-54.

Yan, X., Radwan, E., and Abedl-Aty, M. “Characteristics of rear-end accidents at signalized intersections using multiple logistic regression model,” Accident Analysis and Prevention, 37, 2005, 983-995.

Yu, W., and Lo, S. “Time Dependent Construction Social Costs Model,” Construction Management and Economics, 23:3, 2005, 327-337.

Appendix B: Results from Sensitivity Analyses

This section describes the results, shown using tables and graphs in the following pages, of the sensitivity analysis of the Florida’s Project Level Analysis Tool (PLAT) and Network Analysis Tool (NAT).

Variable:	**Deck replacement scoping rule active**										Appendix B15

	Number of candidates selected in each action category							Total	Total	Total	5-year
Value	0	100	200	300	400	500	600	Cost	Benefit	B/C	Health Ix
1.0	924	110	2	4	23	34	85	101631	246724	2.428	87.3
0.0	922	112	2	4	23	34	85	101973	246805	2.420	87.3

NOTE: All results are for a 10% sample of the Florida bridge inventory

Variable:	Quantity prediction, applicability, and output level										Appendix B16
	Number of candidates selected in each action category							Total	Total	Total	5-year
Value	0	100	200	300	400	500	600	Cost	Benefit	B/C	Health Ix
1	658	290	6	3	102	38	85	102162	252035	2.467	87.3
2	940	99	2	2	20	34	85	100626	246015	2.445	87.2
3	923	111	2	4	23	34	85	101895	246780	2.422	87.3
4	924	110	2	4	23	34	85	101631	246724	2.428	87.3
5	924	110	2	4	23	34	85	101631	246724	2.428	87.3

NOTE: All results are for a 10% sample of the Florida bridge inventory

Appendix C: Analyses of Cost Data by MMS Activity Number

This section describes some of the results from the research effort on validation of bridge costs.

A statistical review and analyses of the MMS Activity Number was done relative to the Pontis Action Subcategory Numbers. First the definitions of the MMS Activity Numbers related to bridge work, are shown in Table C1 as well as the assignment of MMS Activity Numbers to Pontis Element work (Table C2), as currently used by FDOT State Maintenance Office.

Table C1. Definition of MMS activities related to bridge work.

MMS Activity No.	Description	UNITS
805	Bridge Joint Repair	Linear Feet (LF)
806	Bridge Deck Maintenance And Repair	Square Feet (SF)
810	Bridge Handrail Maintenance And Repair	Linear Feet (LF)
825	Superstructure Maintenance And Repair	ManHours (MH)
845	Substructure Maintenance And Repair	ManHours (MH)
859	Channel Maintenance	ManHours (MH)
861	Routine Bridge Electrical Maintenance	ManHours (MH)
865	Routine Bridge Mechanical Maintenance	ManHours (MH)
869	Movable Bridge Structural Maintenance	ManHours (MH)
888	Bridge Damage Repair	ManHours (MH)
898	Tunnel Maintenance	ManHours (MH)
996	Miscellaneous Routine Maintenance	ManHours (MH)

With the objective of suggesting refinement, if any, to FDOT, the relationship between MMS Activity Numbers and assigned Pontis Action Subcategories are shown in Tables C3 to C11. As expected, MMS Activity No 805 (Bridge Joint Repair) comprises mostly, about 80% of element actions done on bridge joints (Action Subcategory Nos. 111, 112, 311, and 411). Predominant element actions in MMS Activity No. 806 (Bridge Deck Maintenance and Repair) are Action Subcategory Nos. 301, 346, and 423 which are related to bridge deck maintenance, approach roadways, and cleaning drainage systems, respectively. MMS Activity No. 810 (Bridge Handrail Maintenance) comprises mostly of repair actions for handrails (Action Subcategory No. 314) and repairs of guardrails, barriers, and parapets (Action Subcategory No. 371). While MMS Activity No. 825 (Superstructure Maintenance and Repair) covered many element actions, over half of the actions observed were related to repair of beams (No. 341). Repair of slope pavement and substructure (Action Subcategory Nos. 321 and 344 respectively) dominate actions under MMS Activity No 845 (Substructure Maintenance and Repair), as well some significant number of actions related to maintenance of slope pavement (Action Subcategory No. 421) and maintenance of beams (Action Subcategory No. 441), with the latter being mostly due to the fact that caps are classified as beams under the Action Subcategory scheme.

Table C2. FDOT guide for matching MMS Activity Nos. to Pontis bridge elements

Elemkey	Element Description	MMS Activity No.	Work Performed On
12	Concrete Deck - Bare	806	Decks/Slabs
13	Concrete Deck - Unprotected w/ AC Overlay	806	Decks/Slabs
28	Steel Deck - Open Grid	806	Decks/Slabs
29	Steel Deck - Concrete Filled Grid	806	Decks/Slabs
30	Steel Deck - Corrugated/Orthotropic/Etc.	806	Decks/Slabs
31	Timber Deck - Bare	806	Decks/Slabs
32	Timber Deck - w/ AC Overlay	806	Decks/Slabs
38	Concrete Slab - Bare	806	Decks/Slabs
39	Concrete Slab - Unprotected w/ AC Overlay	806	Decks/Slabs
54	Timber Slab	806	Decks/Slabs
55	Timber Slab - w/ AC Overlay	806	Decks/Slabs
98	Concrete Deck on Precast Deck Panels	806	Decks/Slabs
99	Prestressed Concrete Slab (Sonovoid)	806	Decks/Slabs
101	Unpainted Steel Closed Web/Box Girder	▨	▨
102	Painted Steel Closed Web/Box Girder	825	Superstructure
104	P/S Conc Closed Web/Box Girder	825	Superstructure
105	Reinforced Concrete Closed Webs/Box Girder	825	Superstructure
106	Unpainted Steel Open Girder/Beam	825	Superstructure
107	Painted Steel Open Girder/Beam	825	Superstructure
109	P/S Conc Open Girder/Beam	825	Superstructure
110	Reinforced Conc Open Girder/Beam	825	Superstructure
111	Timber Open Girder/Beam	▨	▨
112	Unpainted Steel Stringer	▨	▨
113	Painted Steel Stringer	825	Superstructure
115	P/S Conc Stringer	▨	▨
116	Reinforced Conc Stringer	825	Superstructure
117	Timber Stringer	▨	▨
120	Unpainted Steel Bottom Chord Thru Truss	825	Superstructure
121	Painted Steel Bottom Chord Thru Truss	825	Superstructure
125	Unpainted Steel Thru Truss (excl. bottom chord)	▨	▨
126	Painted Steel Thru Truss (excl. bottom chord)	825	Superstructure
130	Unpainted Steel Deck Truss	▨	▨
131	Painted Steel Deck Truss	825	Superstructure
135	Timber Truss/Arch	▨	▨
140	Unpainted Steel Arch	▨	▨
141	Painted Steel Arch	▨	▨
143	P/S Conc Arch	▨	▨
144	Reinforced Conc Arch	825	Superstructure
145	Other Arch	▨	▨
146	Cable - Uncoated (not embedded in concrete)	▨	▨
147	Cable - Coated (not embedded in concrete)	825	Superstructure
151	Unpainted Steel Floor Beam	825	Superstructure
152	Painted Steel Floor Beam	825	Superstructure
154	P/S Conc Floor Beam	▨	▨
155	Reinforced Conc Floor Beam	825	Superstructure
156	Timber Floor Beam	▨	▨
160	Unpainted Steel Pin and/or Pin and Hanger Assembly	▨	▨

Table C2. FDOT guide for matching MMS Activity Nos. to Pontis bridge elements (continued)

Elemkey	Element Description	MMS Activity No.	Work Performed On
161	Painted Steel Pin and/or Pin and Hanger Assembly	825	Superstructure
201	Unpainted Steel Column or Pile	845	Substructure
202	Painted Steel Column or Pile	845	Substructure
204	P/S Conc Column or Pile	845	Substructure
205	Reinforced Conc Column or Pile	845	Substructure
206	Timber Column or Pile	845	Substructure
207	Hollow Core Pile	845	Substructure
210	Reinforced Conc Pier Wall	845	Substructure
211	Other Material Pier Wall	▨	▨
215	Reinforced Conc Abutment	845	Substructure
216	Timber Abutment	845	Substructure
217	Other Material Abutment	845	Substructure
220	Pile Cap/Footing	845	Substructure
225	Unpnt Stl Submd Pile	▨	▨
226	P/S Conc Submgd Pile	▨	▨
227	R/C Submerged Pile	▨	▨
228	Timb Submerged Pile	▨	▨
230	Unpainted Steel Cap	845	Substructure
231	Painted Steel Cap	845	Substructure
233	P/S Conc Cap	845	Substructure
234	Reinforced Conc Cap	845	Substructure
235	Timber Cap	845	Substructure
240	Metal Culvert	845	Substructure
241	Reinforced Concrete Culvert	845	Substructure
242	Timber Culvert	▨	▨
243	Other Culvert	▨	▨
290	Channel	859	Channel Maintenance
298	Pile Jacket without Cathodic Protection	845	Substructure
299	Pile Jacket with Cathodic Protection	845	Substructure
300	Strip Seal Expansion Joint	805	Joints
301	Pourable Joint Seal	805	Joints
302	Compression Joint Seal	805	Joints
303	Assembly Joint/Seal (modular)	805	Joints
304	Open Expansion Joint	805	Joints
310	Elastomeric Bearing	825	Superstructure
311	Moveable Bearing (roller, sliding, etc.)	825	Superstructure
312	Enclosed/Concealed Bearing	825	Superstructure
313	Fixed Bearing	825	Superstructure
314	Pot Bearing	825	Superstructure
315	Disk Bearing	▨	▨
320	P/S Concrete Approach Slab w/ or w-o/AC Ovly	▨	▨
321	Reinforced Conc Approach Slab w/ or w/o AC Ovly	807	▨
330	Metal Bridge Railing - Uncoated	810	Hand Rail
331	Reinforced Conc Bridge Railing	810	Hand Rail
332	Timber Bridge Railing	810	Hand Rail
333	Other Bridge Railing	810	Hand Rail
334	Metal Bridge Railing - Coated	810	Hand Rail
356	Steel Fatigue	▨	▨
357	Pack Rust	▨	▨
358	Deck Cracking	▨	▨
359	Soffit of Concrete Deck or Slab	▨	▨
360	Settlement	▨	▨
361	Scour	▨	▨
362	Traffic Impact	▨	▨
363	Section Loss	▨	▨
369	Substructure Section Loss	▨	▨
370	Alert	▨	▨

Table C2. FDOT guide for matching MMS Activity Nos. to Pontis Bridge elements (Continued)

Elemkey	Element Description	MMS Activity No.	Work Performed On
386	Fender Dolphin System Metal Uncoated	859	Channel Maintenance
387	Fender Dolphin System Prestressed Concrete	859	Channel Maintenance
388	Fender Dolphin System Reinforced Concrete	▨	▨
389	Fender Dolphin System Timber	859	Channel Maintenance
390	Fender Dolphin System Other Material	859	Channel Maintenance
393	Bulkhead/Seawall Metal Uncoated	859	Channel Maintenance
394	Abutment Slope Protection Reinforced Concrete	845	Substructure
395	Abutment Slope Protection Timber	▨	▨
396	Abutment Slope Protection Other Material	845	Substructure
397	Drainage System Metal Coated	808	▨
398	Drainage Sytem Other Material	809	▨
399	Other Expansion Joint	805	Joints
474	Wingwall/Retaining Wall Metal Uncoated	▨	▨
475	Wingwall/Retaining Wall Reinforced Concrete	845	Substructure
476	Wingwall/Retaining Wall Timber	845	Substructure
477	Wingwall/Retaining Wall Other Material	845	Substructure
478	Mechanically Stabilized Earth Wall	845	Substructure
480	Mast Arm Foundations	▨	▨
481	Painted Mast Arm Vertical Member	▨	▨
482	Galvanized Mast Arm Vertical Member	▨	▨
483	Other Mast Arm Vertical Member	▨	▨
484	Painted Mast Arm Horizontal Member	▨	▨
485	Galvanized Mast Arm Horizontal Member	▨	▨
486	Other Mast Arm Horizontal Member	▨	▨
487	Overlane Sign Structure Horizontal Member Metal Co	▨	▨
488	Overlane Sign Structure Vertical Member Metal Coat	▨	▨
489	Overlane Sign Structure Foundation	▨	▨
495	High Mast Light Poles Metal Uncoated	▨	▨
496	High Mast Light Poles Metal Coated	▨	▨
497	High Mast Light Poles Galvanized	▨	▨
498	High Mast Light Poles Other Material	▨	▨
499	High Mast Light Pole Foundations	▨	▨
540	Open Gearing	▨	▨
541	Speed Reducers	▨	▨
542	Shafts	▨	▨
543	Shaft Bearings and Shaft Couplings	▨	▨
544	Brakes	▨	▨
545	Emergency Drive and Back Up Power System	▨	▨
546	Span Drive Motors	▨	▨
547	Hydraulic Power Units	▨	▨
548	Hydraulic Piping System	▨	▨
549	Hydraulic Cylinders/Motors/Rotary Actuators	▨	▨
550	Hopkins Frame	▨	▨
560	Span Locks/Toe Locks/Heel Stops/Tail Locks	▨	▨
561	Live Load Shoes/Strike Plates/Buffer Cylinders	▨	▨
562	Counterweight Support	▨	▨
563	Access Ladder & Platforms	▨	▨
564	Counterweight	▨	▨
565	Trunnion/Straight and Curved Track	▨	▨
570	Transformers & Thyristors	▨	▨
571	Submarine Cable	▨	▨
572	Conduit & Junction Boxes	▨	▨
573	Programmable Logic Controllers	▨	▨
574	Control Console	▨	▨
580	Navigational Light System	▨	▨
581	Operator Facilities	▨	▨
582	Lift Bridge Specific Equipment	▨	▨
583	Swing Bridge Specific Equipment	▨	▨
590	Resistance Barriers	▨	▨
591	Warning Gates	▨	▨
592	Traffic Signal	▨	▨

MMS Activity No. 859 (Channel Maintenance) consists mostly of element Action Subcategory Nos. 321, 344, and 445, representing respectively, slope pavement repairs, beam repairs, and maintenance of culverts. Though not shown in the tables, MMS Activity nos. 861 (Routine Bridge Electrical Maintenance), 865 (Routine Bridge Mechanical Maintenance), and 869 (Movable Bridge Structural Maintenance) were all observed to element Action Subcategory No. 331, i.e., repair of machinery, as these were electrical repairs or repairs on the movable bridges. MMS Activity No. 888 (Bridge Damage Repair) was found assigned mostly to element Action Subcategory No. 314 (repair of handrails), and No 341 (repair of beams). MMS Activity No. 898 (Channel Maintenance) involved mostly element Action Subcategory No. 331 (machinery repairs). Lastly, MMS Activity No. 996 (Miscellaneous Routine Maintenance) covered several element actions, with slope pavement repairs (Action Subcategory No. 321) and machinery repairs (No. 331) making up about 30% of the actions observed under this activity.

The summary of MMS costs (unadjusted for time to 2009 equivalents) by the MMS Activity numbers are shown in Tables C12 to C14 while the age of bridge for the actions are shown in Table C15. Figures C1 to C4 show the variations and statistical distributions. The results are seriously skewed with large extreme values, considering both In-house and contract costs. The values indicated appear more reasonable for action total costs rather than unit costs, probably because of suspect values entered for the units of work done, making the computed unit costs either too high or too low. It would be therefore suggested that the action costs be used rather than the unit costs. A study of relationship between the MMS Activity Costs and the bridge attributes indicated minimal correlation but the age of bridge at the action were observed to be mildly correlated to some bridge attributes, especially the type of superstructure material as shown in Figures C5 and C6.

A detailed FDOT report for the 2006/2007 fiscal year on the In-House costs captured in the MMS was also reviewed. In this report, the average for the MMS Activity Nos. 805, 806, and 810 were found to about $25/LF, $12/LF, and $17/LF respectively (Table C16). Another report of interest is the FDOT's internal method of computing the unit costs. According to MMS Report on Crew Information for fiscal year 2008/09 from jul01 2008 to jun30 2009, area 238 site 9190771 8106689 8067766 (District 2 Jacksonville Office), the labor costs are estimated as follows:

Direct cost = man-hours * hourly rate; Fringe Cost = Direct cost * 0.5654; overhead cost = direct cost * 0.1386; and inmates are paid 6.79/hr. with overhead rate of 0.1386. (no fringe for inmates).

Material costs are estimated as quantity used * Item unit cost* 1.184 (implying a material overhead of 0.184). Only major items are included in materials' costs.

Equipment cost is computed from a Fleetcode rate which is monthly rate divided by average monthly utilization plus operating rate. Equipment cost = usage hours * Fleetcode rate. MH/unts estimated as necessary based on hours and units done.

Since many activities are estimated in $/MH, the information above may be helpful in estimating or converting the MMS costs to the units required for the action costs for Pontis. An attempt was made in estimating unit cots based on MH/Unit values from the FDOT MMS Reports, but unfortunately, the MH/Unit values are not consistent, as shown in Table C17.

Table C3. Composition of MMS Activity No. 805 in terms of action subcategories

Action Subcategory	Count	% of MMS Activity Count	Action Cost ($)	% of MMS Activity Cost
111	132	5.8%	90,125.59	4.7%
112	**586**	**25.8%**	**386,282.19**	**20.3%**
114	1	0.0%	81.08	0.0%
300	0	0.0%	0.00	0.0%
303	20	0.9%	18,537.53	1.0%
311	**1106**	**48.8%**	**1,111,380.61**	**58.5%**
321	184	8.1%	22,457.98	1.2%
323	9	0.4%	119.23	0.0%
346	118	5.2%	20,859.53	1.1%
411	74	3.3%	26,784.05	1.4%
421	1	0.0%	9.07	0.0%
422	1	0.0%	219.63	0.0%
999	**36**	**1.6%**	**222,963.57**	**11.7%**
0	0	0.0%	0.00	0.0%
TOTALS	2268	100.0%	1,899,820.08	100.0%

* Action Subcategories 999 and 0 are unmatched or blank assignments

Table C4. Composition of MMS Activity No. 806 in terms of action subcategories

Action Subcategory	Count	% of MMS Activity Count	Action Cost ($)	% of MMS Activity Cost
111	1	0.0%	894.75	0.0%
114	3	0.1%	174.12	0.0%
123	2	0.1%	657.67	0.0%
151	1	0.0%	292.05	0.0%
201	1	0.0%	4,488.76	0.2%
223	1	0.0%	54.58	0.0%
231	1	0.0%	563.65	0.0%
246	1	0.0%	1.60	0.0%
301	**802**	**32.2%**	**888,304.31**	**47.8%**
303	64	2.6%	45,674.25	2.5%
311	**183**	**7.3%**	**223,001.90**	**12.0%**
314	4	0.2%	613.02	0.0%
321	4	0.2%	749.17	0.0%
323	44	1.8%	21,269.42	1.1%
331	12	0.5%	11,509.94	0.6%
341	3	0.1%	2,364.45	0.1%
344	5	0.2%	954.46	0.1%
346	**516**	**20.7%**	**342,055.69**	**18.4%**
351	9	0.4%	4,463.16	0.2%
371	6	0.2%	23,335.21	1.3%
400	13	0.5%	2,188.47	0.1%
401	103	4.1%	14,132.45	0.8%
411	58	2.3%	4,256.83	0.2%
421	2	0.1%	22.23	0.0%
422	5	0.2%	9,446.22	0.5%
423	**513**	**20.6%**	**146,428.04**	**7.9%**
431	3	0.1%	98.36	0.0%
441	1	0.0%	86.92	0.0%
444	7	0.3%	591.02	0.0%
445	2	0.1%	2,167.06	0.1%
446	16	0.6%	6,856.42	0.4%
451	3	0.1%	392.75	0.0%
999	30	1.2%	8,570.05	0.5%
0	75	3.0%	91,812.12	4.9%
TOTALS	2494	100.0%	1,858,471.08	100.0%

* Action Subcategories 999 and 0 are unmatched or blank assignments

Table C5. Composition of MMS Activity No. 810 in terms of action subcategories

Action Subcategory	Count	% of MMS Activity Count	Action Cost ($)	% of MMS Activity Cost
114	16	2.2%	23,044.07	5.2%
151	3	0.4%	1,109.59	0.2%
301	10	1.3%	2,281.39	0.5%
303	42	5.7%	20,034.54	4.5%
311	3	0.4%	191.73	0.0%
314	**316**	**42.6%**	**144,984.86**	**32.6%**
331	14	1.9%	2,007.42	0.5%
341	1	0.1%	3,102.19	0.7%
344	10	1.3%	6,566.75	1.5%
346	6	0.8%	1,159.83	0.3%
351	43	5.8%	13,140.98	3.0%
361	1	0.1%	353.76	0.1%
371	**222**	**29.9%**	**162,001.69**	**36.4%**
400	5	0.7%	863.22	0.2%
414	2	0.3%	307.63	0.1%
431	1	0.1%	87.85	0.0%
471	4	0.5%	154.17	0.0%
0	**43**	**5.8%**	**63,482.89**	**14.3%**
TOTALS	742	100.0%	444,874.57	100.0%

* Action Subcategory 0 are unmatched or blank assignments

Table C6. Composition of MMS Activity No. 825 in terms of action subcategories

Action Subcategory	Count	% of MMS Activity Count	Action Cost ($)	% of MMS Activity Cost
113	3	0.2%	1,381.83	0.1%
141	1	0.1%	232.07	0.0%
151	15	0.9%	5,408.28	0.2%
301	**103**	**6.3%**	**428,299.42**	**18.2%**
303	44	2.7%	133,627.38	5.7%
311	**27**	**1.7%**	**386,083.70**	**16.4%**
313	65	4.0%	44,252.82	1.9%
314	30	1.8%	69,522.85	3.0%
321	1	0.1%	2.85	0.0%
323	2	0.1%	2,671.68	0.1%
331	100	6.1%	43,675.02	1.9%
332	1	0.1%	10,250.24	0.4%
341	**903**	**55.4%**	**958,926.47**	**40.8%**
344	33	2.0%	15,936.18	0.7%
345	1	0.1%	9.07	0.0%
346	15	0.9%	26,172.94	1.1%
351	8	0.5%	10,104.30	0.4%
361	3	0.2%	15,759.67	0.7%
371	38	2.3%	54,620.58	2.3%
400	9	0.6%	3,703.17	0.2%
401	2	0.1%	1,962.65	0.1%
402	7	0.4%	654.52	0.0%
411	2	0.1%	1,314.57	0.1%
413	19	1.2%	11,607.64	0.5%
414	2	0.1%	3.97	0.0%
423	3	0.2%	567.80	0.0%
431	2	0.1%	176.44	0.0%
441	88	5.4%	42,693.30	1.8%
444	7	0.4%	712.84	0.0%
451	32	2.0%	8,184.22	0.3%
471	2	0.1%	20.68	0.0%
0	62	3.8%	70,063.72	3.0%
TOTALS	1630	100.0%	2,348,602.88	100.0%

* Action Subcategory 0 are unmatched or blank assignments

Table C7. Composition of MMS Activity No. 845 in terms of action subcategories

Action Subcategory	Count	% of MMS Activity Count	Action Cost ($)	% of MMS Activity Cost
111	1	0.0%	27.02	0.0%
113	2	0.0%	54.91	0.0%
114	1	0.0%	1,035.18	0.0%
121	4	0.1%	298.50	0.0%
123	1	0.0%	669.08	0.0%
144	3	0.1%	60,723.63	1.6%
144	3	0.1%	60,723.63	1.6%
151	5	0.1%	1,543.21	0.0%
221	2	0.0%	25,186.65	0.7%
301	23	0.5%	7,325.19	0.2%
303	32	0.7%	23,911.21	0.6%
306	9	0.2%	2,697.05	0.1%
311	18	0.4%	17,946.80	0.5%
313	19	0.4%	663,165.71	17.1%
314	6	0.1%	519.40	0.0%
321	**1630**	**34.8%**	**1,519,824.72**	**39.3%**
323	28	0.6%	6,172.19	0.2%
331	52	1.1%	18,994.24	0.5%
332	38	0.8%	53,256.11	1.4%
334	0	0.0%	0.00	0.0%
341	338	7.2%	226,358.12	5.9%
344	**788**	**16.8%**	**695,884.32**	**18.0%**
345	122	2.6%	56,846.21	1.5%
346	94	2.0%	35,201.12	0.9%
351	13	0.3%	1,869.02	0.0%
371	22	0.5%	8,475.40	0.2%
400	90	1.9%	30,928.38	0.8%
401	15	0.3%	669.66	0.0%
403	2	0.0%	7,388.99	0.2%
406	38	0.8%	6,645.62	0.2%
411	7	0.1%	702.43	0.0%
413	15	0.3%	2,144.20	0.1%
414	1	0.0%	695.20	0.0%
421	**448**	**9.6%**	101,217.81	2.6%
422	6	0.1%	67.62	0.0%
423	26	0.6%	10,448.79	0.3%
431	9	0.2%	1,927.07	0.0%
432	1	0.0%	169.28	0.0%
441	**449**	**9.6%**	96,773.29	2.5%
444	178	3.8%	47,194.59	1.2%
445	65	1.4%	19,888.81	0.5%
446	7	0.1%	546.48	0.0%
451	3	0.1%	191.64	0.0%
471	1	0.0%	13.03	0.0%
0	75	1.6%	51,966.59	1.3%
TOTALS	4690	100.0%	3,868,288.10	100.0%

* Action Subcategory 0 are unmatched or blank assignments

Table C8. Composition of MMS Activity No. 859 in terms of action subcategories

Action Subcategory	Count	% of MMS Activity Count	Action Cost ($)	% of MMS Activity Cost
114	1	0.1%	6,567.89	0.7%
121	3	0.3%	6,146.89	0.6%
131	2	0.2%	1,733.12	0.2%
151	4	0.4%	3,880.17	0.4%
301	3	0.3%	2,714.60	0.3%
303	2	0.2%	3,413.80	0.3%
314	8	0.7%	9,229.96	0.9%
321	**322**	**28.3%**	**97,502.50**	**9.9%**
322	15	1.3%	3,867.89	0.4%
323	1	0.1%	39.07	0.0%
331	94	8.3%	78,431.47	7.9%
341	16	1.4%	4,347.83	0.4%
344	**158**	**13.9%**	**523,333.50**	**52.9%**
345	112	9.8%	62,015.38	6.3%
351	20	1.8%	8,086.31	0.8%
400	100	8.8%	40,344.32	4.1%
414	1	0.1%	37.45	0.0%
421	21	1.8%	685.68	0.1%
422	77	6.8%	30,212.09	3.1%
431	3	0.3%	3,209.28	0.3%
444	19	1.7%	27,378.30	2.8%
445	**136**	**12.0%**	**52,660.39**	**5.3%**
451	2	0.2%	174.37	0.0%
0.00	18	1.6%	22,862.03	2.3%
TOTALS	1138	100.0%	988,874.27	100.0%

* Action Subcategory 0 are unmatched or blank assignments

Table C9. Composition of MMS Activity No. 888 in terms of action subcategories

Action Subcategory	Count	% of MMS Activity Count	Action Cost ($)	% of MMS Activity Cost
301	3	3.4%	143.38	0.3%
314	**25**	**28.4%**	**17,184.23**	**39.2%**
331	2	2.3%	29.13	0.1%
341	**38**	**43.2%**	**15,264.67**	**34.9%**
344	3	3.4%	926.81	2.1%
346	1	1.1%	5.98	0.0%
351	3	3.4%	477.15	1.1%
361	4	4.5%	125.89	0.3%
371	**7**	**8.0%**	**9,512.26**	**21.7%**
401	1	1.1%	120.67	0.3%
0.00	1	1.1%	0.69	0.0%
TOTALS	88	100.0%	43,790.87	100.0%

* Action Subcategory 0 are unmatched or blank assignments

Table C10. Composition of MMS Activity No. 898 in terms of action subcategories

Action Subcategory	Count	% of MMS Activity Count	Action Cost ($)	% of MMS Activity Cost
314	2	8.3%	525.75	3.3%
321	2	8.3%	415.33	2.6%
331	**16**	**66.7%**	**11,451.27**	**71.0%**
400	2	8.3%	20.98	0.1%
0	2	8.3%	**3,726.27**	**23.1%**
TOTALS	24	100.0%	16,139.59	100.0%

* Action Subcategory 0 are unmatched or blank assignments

Table C11. Composition of MMS Activity No. 996 in terms of action subcategories

Action Subcategory	Count	% of MMS Activity Count	Action Cost ($)	% of MMS Activity Cost
111	1	0.1%	14.92	0.0%
123	1	0.1%	118.55	0.0%
151	10	0.9%	1,746.85	0.5%
171	4	0.4%	4,867.65	1.3%
301	19	1.7%	4,535.45	1.2%
303	9	0.8%	1,187.58	0.3%
311	10	0.9%	13,573.31	3.5%
313	3	0.3%	12,078.14	3.1%
314	22	2.0%	10,259.47	2.7%
321	**143**	**13.1%**	**74,418.48**	**19.4%**
323	26	2.4%	11,596.65	3.0%
331	**161**	**14.7%**	**38,470.50**	**10.0%**
332	1	0.1%	33.06	0.0%
341	33	3.0%	17,436.86	4.5%
344	**27**	**2.5%**	**10,635.04**	**2.8%**
345	7	0.6%	3,382.49	0.9%
346	40	3.7%	19,651.62	5.1%
351	87	8.0%	20,341.00	5.3%
352	0	0.0%	0.00	0.0%
371	75	6.9%	26,803.46	7.0%
400	41	3.8%	11,390.82	3.0%
401	13	1.2%	7,743.10	2.0%
406	1	0.1%	33.51	0.0%
411	6	0.5%	2,096.45	0.5%
414	1	0.1%	5.69	0.0%
421	53	4.9%	7,923.54	2.1%
422	3	0.3%	309.82	0.1%
423	16	1.5%	14,245.16	3.7%
431	12	1.1%	2,825.42	0.7%
441	70	6.4%	8,085.85	2.1%
444	45	4.1%	3,336.97	0.9%
445	11	1.0%	16,116.08	4.2%
446	9	0.8%	2,037.22	0.5%
451	40	3.7%	10,705.95	2.8%
471	1	0.1%	56.09	0.0%
0	91	8.3%	25,376.24	6.6%
TOTALS	1092	100.0%	383,438.97	100.0%

* Action Subcategory 0 are unmatched or blank assignments

Table C12. Estimated values for in-house unit costs per bridge action

MMS ACT NO. UNIT.	COSTS ($/UNIT)					COUNT
	MEAN	STD DEV	MIN	MAX	MEDIAN	
805LF	272.48	842.80	0.01	20,353.57	28.76	1345
805LM	438.83	762.42	0.03	6,506.21	150.92	199
805MH	185.25	222.75	0.15	655.72	84.88	11
805SF	213.75	191.18	58.17	555.94	147.42	7
806CF	86.62	107.21	0.90	400.66	40.27	22
806EA	215.34	260.23	3.04	697.59	93.90	12
806LF	70.71	215.38	0.58	786.22	8.41	13
806MH	126.51	283.18	0.00	2,770.28	32.25	722
806SF	257.30	546.05	0.00	6,126.25	83.29	1019
806SM	441.20	642.79	0.03	4,940.91	244.43	353
806SY	470.68	427.69	64.30	1,417.09	358.67	8
810LF	220.55	618.42	0.03	7,276.08	60.12	537
810LM	511.91	751.13	0.44	3,709.38	179.46	90
810MH	91.76	126.01	4.16	478.19	38.38	16
825CF	206.89	324.34	3.41	2,156.45	124.66	54
825EA	113.10	141.65	0.33	364.60	65.63	6
825MH	514.65	1,679.98	0.32	35,121.00	130.62	1265
845CF	359.32	821.62	0.20	3,782.08	74.84	34
845EA	176.63	184.83	14.47	821.54	109.89	27
845LF	425.50	915.35	13.89	3,503.67	94.83	14
845SF	52.91	156.68	0.01	1,244.70	4.43	94
845MH	451.75	6,624.97	0.01	368,066.62	72.36	3183
859SF	30.55	75.59	0.01	433.55	8.14	34
859MH	319.96	772.02	0.01	7,830.31	41.72	960
861MH	107.28	304.99	0.21	4,576.67	23.35	549
865MH	108.99	290.28	0.12	2,878.19	18.81	446
869MH	291.08	535.70	0.08	3,756.16	95.51	317
888MH	1,139.33	1,784.05	14.55	8,659.36	423.44	71
996CY	48.88	39.20	3.80	126.13	48.29	8
996MH	336.88	4,389.04	0.02	121,657.79	31.44	864

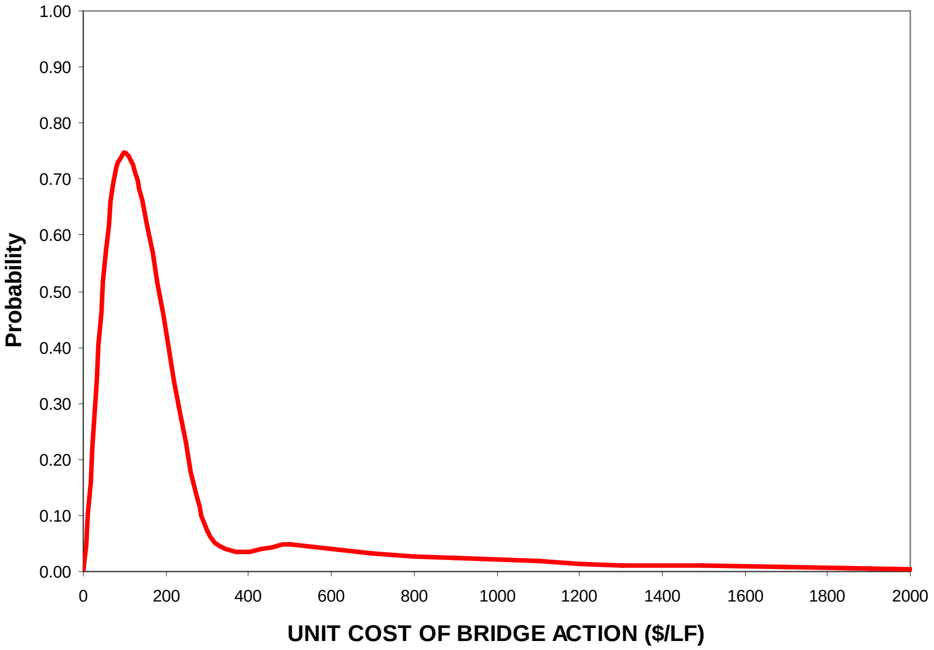


Figure C1. Approximate probability distribution for in-house unit cost per bridge action for MMS ACT 805LF (90th percentile = $800/LF)

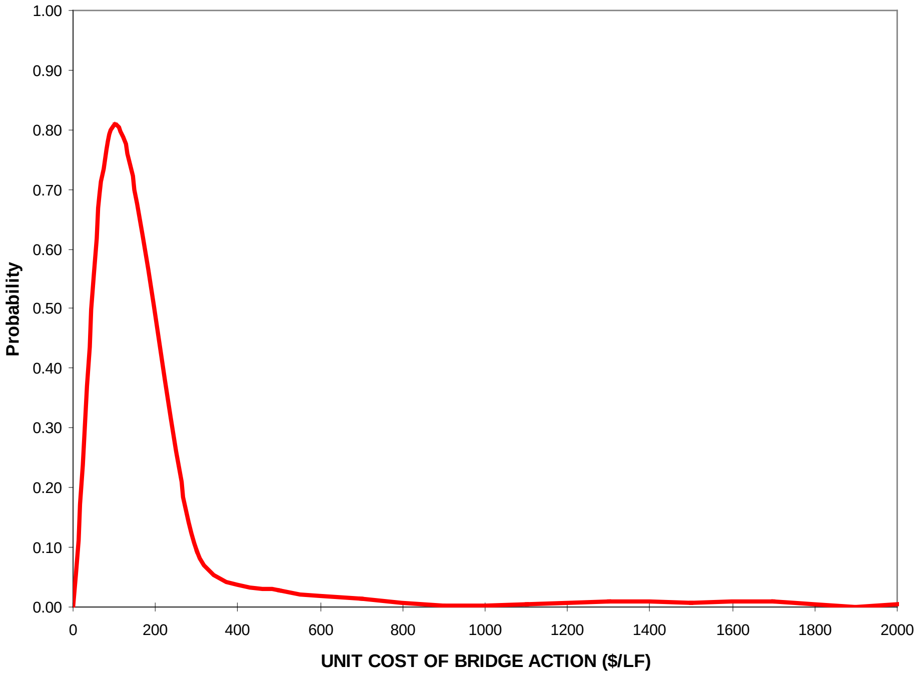


Figure C2. Approximate probability distribution for in-house unit cost per bridge action for MMS ACT 810LF (90th Percentile = $400/LF)

Table C13. Estimated values for in-house total costs per bridge action

MMS ACT NO.	TOTAL COSTS ($)					COUNT
	MEAN	STD DEV	MIN	MAX	MEDIAN	
411	23,155.14	35,650.75	103.00	210,587.91	12,515.28	90
412	24,256.32	28,951.80	693.00	75,095.55	8,576.70	9
421	58,943.61	117,453.73	52.00	502,737.87	9,176.80	29
423	30,127.48	32,587.71	138.32	203,828.41	19,666.72	65
424	40,065.71	48,658.55	466.00	243,938.00	20,100.61	105
425	44,195.26	35,738.08	21,589.00	106,748.33	30,407.48	5
432	22,031.64	40,298.14	116.00	336,090.75	9,056.48	199
437	38,532.74	80,965.93	73.00	610,521.00	10,947.59	162
451	30,953.04	77,891.18	116.00	238,503.47	6,331.98	9
456	32,246.02	40,487.38	230.05	139,775.30	9,839.95	13
457	48,161.69	75,677.54	35.08	628,434.41	23,162.24	329
459	23,433.28	52,072.62	359.00	251,605.20	3,901.77	24
461	164,905.37	269,228.24	415.00	764,750.55	23,899.62	8
464	94,790.48	199,321.14	141.00	566,673.25	1,879.32	8
487	16,923.95	21,275.23	271.00	114,005.37	8,799.50	59
492	15,609.74	20,684.60	487.91	97,948.37	9,521.92	23
494	10,965.32	16,207.29	291.76	113,645.65	7,065.68	60
519	5,761.65	8,493.50	143.00	45,419.20	3,009.59	27
520	7,639.01	9,299.18	64.00	49,853.40	4,384.52	139
521	22,878.32	33,771.10	47.00	145,748.41	9,446.27	41
526	10,998.52	20,072.21	5.00	134,680.91	2,292.13	170
527	16,071.78	21,226.27	544.00	84,135.35	10,566.75	37
532	14,731.47	12,895.99	633.00	31,964.48	17,742.99	7
534	22,702.89	13,121.54	1,399.00	32,515.53	29,780.89	5
537	6,784.33	8,239.34	116.00	50,740.14	5,112.04	54
540	18,076.35	11,918.94	223.05	49,627.86	15,386.13	62
542	18,346.66	18,783.00	478.00	54,899.01	9,299.50	12
787	7,151.27	15,525.55	141.00	122,313.46	2,054.00	115
805	1,259.35	10,371.28	1.41	407,071.30	608.31	1565
806	511.79	1,593.12	1.06	58,966.27	250.48	2160
810	551.45	1,078.59	1.41	10,582.46	183.77	647
825	720.74	2,219.58	1.41	71,366.33	333.48	1332
845	772.40	6,723.46	1.41	368,066.62	257.69	3363
859	309.88	759.89	0.01	7,830.31	39.57	996
861	197.16	737.95	3.71	15,542.14	55.06	553
865	320.15	1,269.02	1.41	23,454.35	64.85	448
869	625.47	2,191.41	4.51	34,659.98	200.23	318
888	1,126.84	1,774.60	8,659.36	81,132.63	418.25	72
898	390.55	584.80	15.79	1,918.85	125.05	24
996	799.93	7,458.23	1.41	136,547.31	171.92	882

Table C14. Estimated values for in-house plus contract total costs per bridge action

MMS ACT NO.	TOTAL COSTS ($)					COUNT
	MEAN	STD DEV	MIN	MAX	MEDIAN	
411	23,155.14	35,650.75	103.00	210,587.91	12,515.28	90
412	24,256.32	28,951.80	693.00	75,095.55	8,576.70	9
421	58,943.61	117,453.73	52.00	502,737.87	9,176.80	29
423	27,218.79	31,856.14	138.32	203,828.41	18,526.41	73
424	33,865.11	45,027.07	466.00	243,938.00	15,931.35	133
425	22,823.13	32,818.92	200.00	106,748.33	13,367.00	10
432	21,980.83	40,203.19	116.00	336,090.75	9,148.62	200
437	38,111.72	80,560.63	73.00	610,521.00	10,947.59	164
451	21,992.13	62,661.58	100.00	238,503.47	5,000.87	14
456	32,246.02	40,487.38	230.05	139,775.30	9,839.95	13
457	43,543.90	73,188.14	35.08	628,434.41	20,002.57	365
459	23,445.43	52,067.03	381.00	251,605.20	3,901.77	24
461	164,905.37	269,228.24	415.00	764,750.55	23,899.62	8
464	94,790.48	199,321.14	141.00	566,673.25	1,879.32	8
487	16,923.95	21,275.23	271.00	114,005.37	8,799.50	59
492	15,609.74	20,684.60	487.91	97,948.37	9,521.92	23
494	10,965.32	16,207.29	291.76	113,645.65	7,065.68	60
519	5,761.65	8,493.50	143.00	45,419.20	3,009.59	27
520	7,584.81	9,287.84	50.00	49,853.40	4,301.45	140
521	17,909.21	31,042.50	47.00	145,748.41	3,703.00	53
526	9,524.88	18,643.14	5.00	134,680.91	1,888.00	205
527	15,790.76	21,007.12	544.00	84,135.35	9,962.93	38
532	14,731.47	12,895.99	633.00	31,964.48	17,742.99	7
534	22,702.89	13,121.54	1,399.00	32,515.53	29,780.89	5
537	6,784.33	8,239.34	116.00	50,740.14	675.00	54
540	17,791.01	12,037.40	100.00	49,627.86	14,015.75	63
542	18,346.66	18,783.00	478.00	54,899.01	9,299.50	12
787	6,556.67	14,952.98	18.00	122,313.46	1,844.50	126
805	2,752.20	10,249.23	1.00	407,071.30	862.67	2,269
806	840.24	2,708.66	1.06	58,966.27	280.87	2,445
810	786.10	2,639.67	1.41	51,700.00	210.68	731
825	904.41	2,722.05	1.41	71,366.33	379.56	1,594
845	1,100.54	6,677.51	0.04	368,066.62	291.36	4540
859	1,738.35	5,662.09	1.16	72,890.00	420.00	1,134
861	187.81	699.75	4.98	15,542.14	54.61	620
865	289.99	1,140.61	1.41	23,454.35	76.43	568
869	594.34	2,096.41	4.51	34,659.98	184.59	350
888	1,330.35	1,826.09	14.55	8,659.36	576.85	88
898	390.55	584.80	15.79	1,918.85	125.05	24
996	778.78	6,760.68	1.41	136,547.31	172.36	1,081

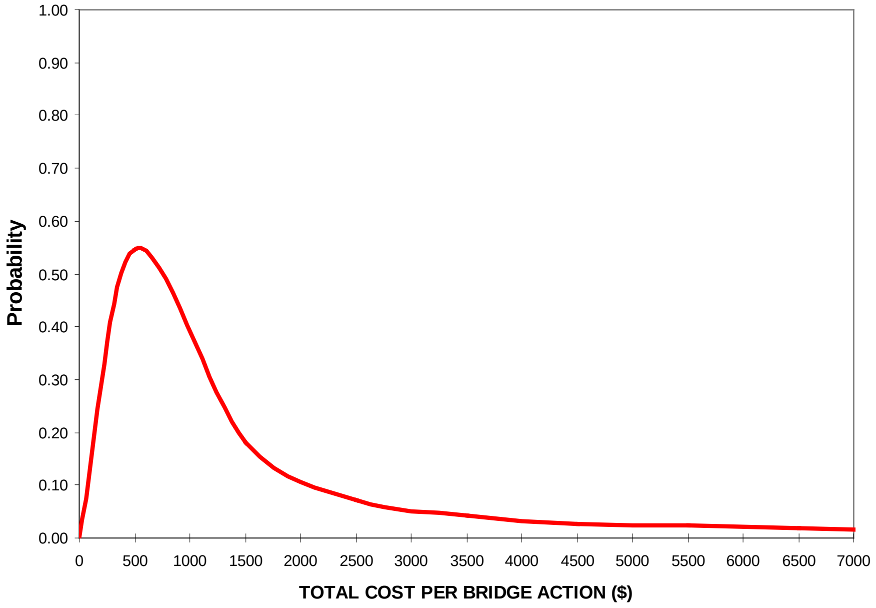


Figure C3. Approximate probability distribution for inhouse+contract total cost per bridge action for MMS ACT 805 (90th Percentile = $7000)

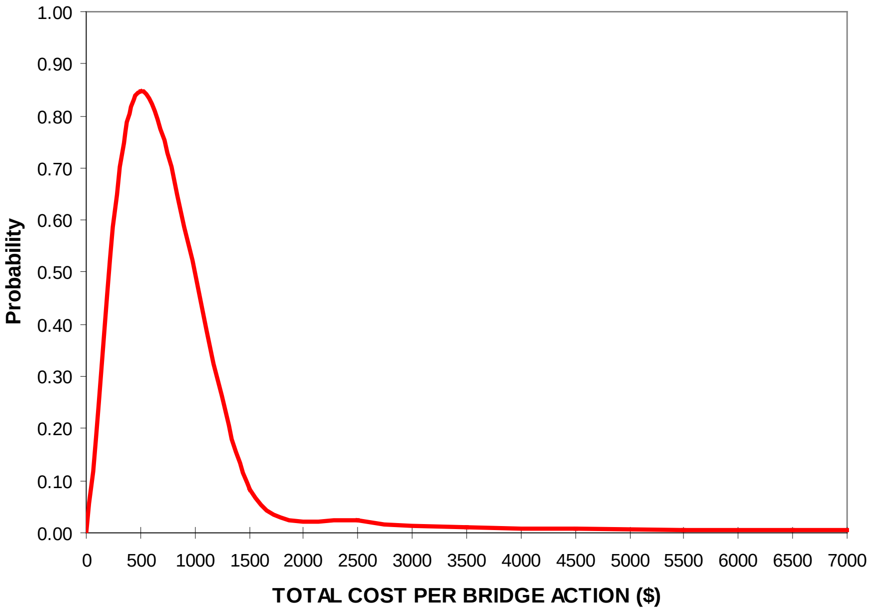


Figure C4. Approximate probability distribution for inhouse+contract total cost per bridge action for MMS ACT 806 (90th Percentile = $2000)

Table C15. Estimated values for timing of bridge actions

MMS ACT NO.	AGE OF BRIDGE AT ACTION (YR.)					COUNT
	MEAN	STD DEV	MIN	MAX	MEDIAN	
411	33.1	14.7	4	72.0	32.5	90
412	28.8	20.4	7	69.0	23.0	9
421	27.1	14.1	3	66.0	25.0	29
423	20.8	11.8	0	56.0	21.0	73
424	26.5	10.4	3	57.0	29.0	133
425	33.0	4.1	27	40.0	32.5	10
432	32.0	14.9	1	71.0	32.0	200
437	29.6	15.8	2	73.0	27.5	164
451	22.1	16.2	5	62.0	19.5	14
456	20.5	11.9	4	42.0	17.0	13
457	33.4	13.2	1	71.0	33.0	365
459	29.3	12.3	5	49.0	32.0	24
461	32.0	13.8	3	43.0	35.5	8
464	31.4	10.7	16	48.0	29.5	8
487	25.3	15.8	5	69.0	22.0	59
492	29.9	13.2	5	70.0	29.0	23
494	25.9	10.9	4	65.0	27.0	60
519	23.7	16.4	7	68.0	15.0	27
520	29.9	13.3	3	71.0	30.0	140
521	20.9	9.5	3	43.0	20.0	53
526	30.0	14.4	3	70.0	30.0	205
527	21.6	11.1	2	47.0	20.5	38
532	28.0	16.9	4	46.0	34.0	7
534	25.6	9.6	9	33.0	30.0	5
537	25.3	9.2	4	45.0	28.0	54
540	27.1	11.1	4	70.0	27.0	63
542	32.7	24.4	11	74.0	23.0	12
787	23.3	11.7	4	59.0	22.0	126
805	25.3	12.9	1	95.0	26.0	2,269
806	28.9	14.7	0	95.0	30.0	2,445
810	28.9	14.2	1	95.0	30.0	731
825	30.3	13.9	1	78.0	31.5	1,594
845	29.1	14.5	0	98.0	30.0	4,542
859	30.7	15.2	1	77.0	30.0	1,134
861	35.1	15.3	1	86.0	38.0	620
865	35.3	13.9	0	88.0	37.0	568
869	35.8	14.9	1	85.0	38.0	350
888	39.1	11.5	1	70.0	37.0	88
898	36.0	6.1	25	58.0	36.0	24
996	28.7	15.0	0	86.0	31.0	1,081

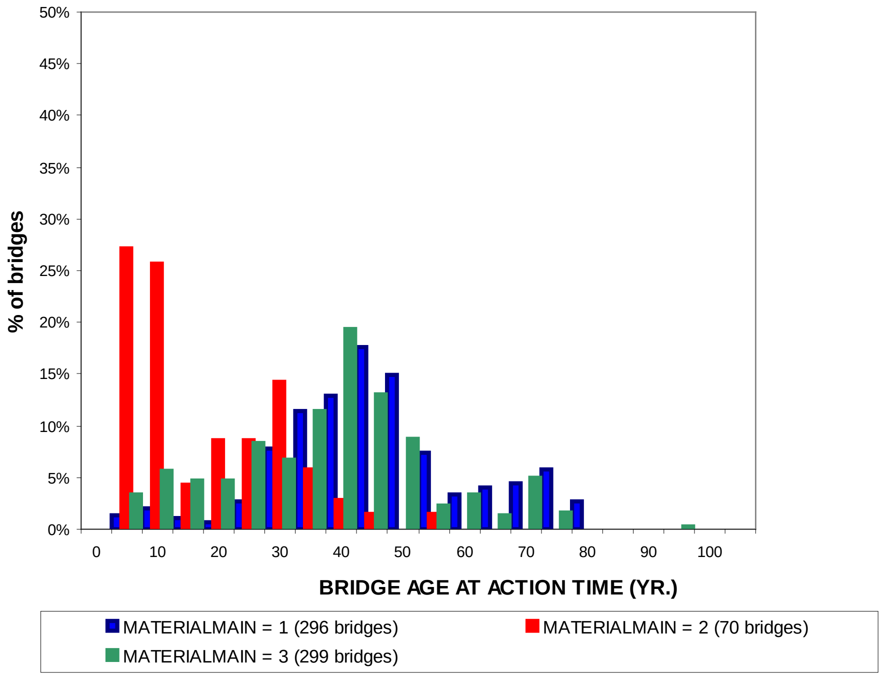


Figure C5. Variation by bridge material type (i) for age of bridge (Yr.) at Action MMS ACT 806

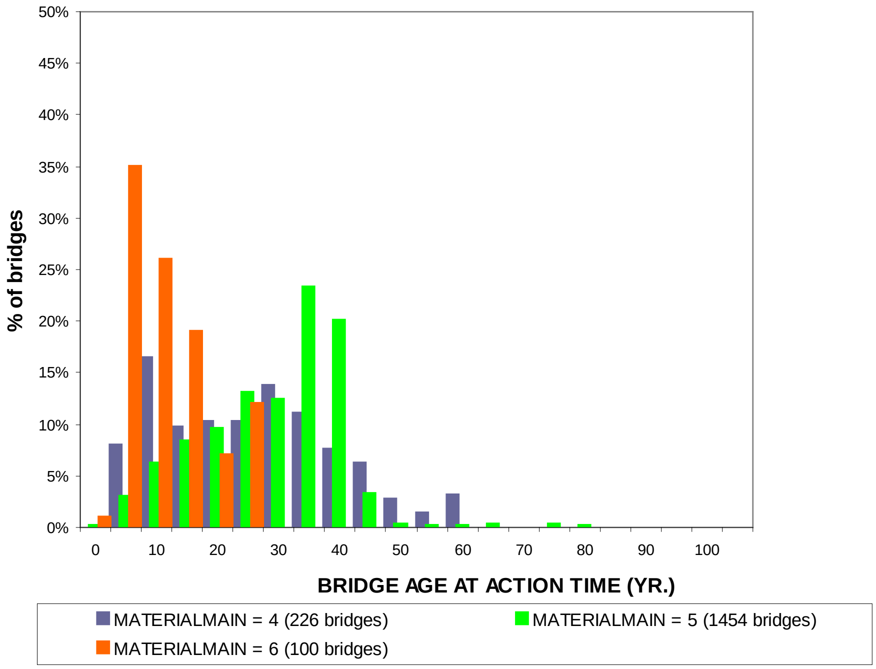


Figure C6. Variation by bridge material type (ii) for age of bridge (Yr.) at Action MMS ACT 806

Table C16. Summary of MMS cost report for in-house 2006-2007 Fiscal Year

MMS Activity No. Unit	COST ($/UNIT)					COUNT
	MEAN	STD. DEV	MIN	MAX	MEDIAN	
805LF	25.3	42.5	0.9	140.4	8.1	16
806SF	12.1	10.6	0.0	32.3	7.7	17
810LF	17.0	20.2	0.0	70.1	10.1	11
825MH	25.6	12.4	14.5	65.9	23.3	14
845MH	29.2	13.6	16.9	78.4	26.1	20
859MH	26.9	8.0	11.6	41.6	25.3	14
861MH	35.8	11.2	25.9	62.5	32.6	8
865MH	29.8	5.1	24.0	33.6	31.8	3
869MH	22.3	4.6	17.1	28.4	21.9	4
888MH	24.3	9.9	17.2	31.3	24.3	2
898MH	22.5	N/A	22.5	22.5	22.5	1
996MH	32.4	11.1	20.9	71.5	28.9	30

Table C17. MMS cost report with detailed unit data for in-house 2006-2007 Fiscal Year

MMSACTNO	DISTRICT	AREA	REGHRS	SAFHRS	UNITS	LABOR $	LAB$/UNIT	EQUIP $	EQP$/UNIT	MAT $	MAT$/UNIT	TOTAL $	$/UNIT	MH/UNIT
805	2	238	1,194	0	2,070	$26,943	$13.02	$3,833	$1.85	$10,928	$5.28	$41,703	$20.15	0.577
805	3	390	44	17	251	$1,315	$5.23	$122	$0.49	$0	$0.00	$1,437	$5.72	0.239
805	3	391	50	0	584	$1,316	$2.25	$212	$0.36	$0	$0.00	$1,528	$2.62	0.086
805	3	392	164	7	1,415	$2,207	$1.56	$132	$0.09	$27	$0.02	$2,366	$1.67	0.121
805	3	393	105	0	2,234	$1,798	$0.80	$230	$0.10	$0	$0.00	$2,028	$0.91	0.047
805	3	395	593	118	1,879	$14,832	$7.90	$1,947	$1.04	$56	$0.03	$16,835	$8.96	0.378
805	4	490	925	46	6,445	$21,444	$3.33	$4,067	$0.63	$25,967	$4.03	$51,479	$7.99	0.151
805	4	491	4	0	2	$50	$24.90	$42	$20.80	$0	$0.00	$91	$45.70	2.000
805	5	590	33	0	377	$532	$1.41	$196	$0.52	$330	$0.88	$1,059	$2.81	0.088
805	5	591	352	11	1,469	$9,054	$6.17	$1,258	$0.86	$1,700	$1.16	$12,012	$8.18	0.247
805	5	592	102	28	418	$2,613	$6.26	$257	$0.61	$1,304	$3.12	$4,174	$9.99	0.311
805	5	593	39	6	136	$931	$6.85	$93	$0.69	$18,071	$132.87	$19,095	$140.41	0.327
805	5	594	570	279	7,898	$18,671	$2.36	$1,978	$0.25	$13,553	$1.72	$34,202	$4.33	0.107
805	6	690	264	32	652	$7,152	$10.97	$1,140	$1.75	$3,396	$5.21	$11,688	$17.92	0.454
805	6	691	11	4	40	$287	$7.17	$0	$0.00	$0	$0.00	$287	$7.17	0.375
805	6	692	2	0	1	$78	$78.00	$42	$41.82	$0	$0.00	$120	$119.82	2.000
806	2	238	4,046	69	232,495	$85,463	$0.37	$12,015	$0.05	$11,653	$0.05	$109,132	$0.47	0.018
806	3	390	95	46	490	$2,196	$4.48	$274	$0.56	$0	$0.00	$2,470	$5.04	0.287
806	3	391	190	0	1,383	$5,161	$3.73	$368	$0.27	$6,261	$4.53	$11,790	$8.52	0.137
806	3	392	346	61	1,001	$6,497	$6.49	$1,239	$1.24	$0	$0.00	$7,735	$7.73	0.407
806	3	393	214	0	139,802	$4,457	$0.03	$721	$0.01	$0	$0.00	$5,178	$0.04	0.002
806	3	395	587	155	1,770	$13,724	$7.76	$1,934	$1.09	$2,602	$1.47	$18,260	$10.32	0.419
806	4	438	52	0	52	$1,009	$19.40	$393	$7.56	$0	$0.00	$1,402	$26.95	1.000
806	4	490	185	2	1,012	$4,144	$4.10	$464	$0.46	$0	$0.00	$4,608	$4.56	0.185
806	4	491	198	1	218	$4,704	$21.58	$424	$1.94	$0	$0.00	$5,128	$23.52	0.911
806	5	590	21	0	36	$421	$11.71	$69	$1.92	$0	$0.00	$490	$13.62	0.569
806	5	591	1,102	60	6,234	$28,828	$4.62	$3,323	$0.53	$2,054	$0.33	$34,206	$5.49	0.186
806	5	592	5	0	5	$93	$20.60	$7	$1.60	$0	$0.00	$100	$22.20	1.000
806	5	593	96	5	64	$1,757	$27.26	$237	$3.67	$88	$1.36	$2,081	$32.29	1.551
806	5	594	294	122	357	$9,285	$26.01	$739	$2.07	$514	$1.44	$10,538	$29.52	1.165
806	5	595	18	9	122	$585	$4.80	$319	$2.61	$0	$0.00	$904	$7.41	0.221
806	6	690	255	12	1,276	$6,258	$4.91	$853	$0.67	$292	$0.23	$7,403	$5.80	0.209
806	6	691	218	0	2,222	$4,655	$2.09	$1,091	$0.49	$0	$0.00	$5,746	$2.59	0.098
810	2	238	2,489	92	4,788	$57,237	$11.96	$5,825	$1.22	$1,144	$0.24	$64,206	$13.41	0.539
810	3	390	1	0	0	$47	$0.00	$0	$0.00	$0	$0.00	$47	$0.00	0.000
810	3	392	13	0	300	$170	$0.57	$19	$0.06	$0	$0.00	$189	$0.63	0.043
810	3	395	229	21	650	$4,937	$7.60	$478	$0.74	$0	$0.00	$5,416	$8.33	0.385
810	4	490	1	0	1	$33	$33.41	$1	$0.58	$0	$0.00	$34	$33.99	1.000
810	4	491	30	0	94	$733	$7.80	$217	$2.30	$0	$0.00	$950	$10.11	0.314
810	4	496	8	1	12	$120	$10.03	$0	$0.00	$0	$0.00	$120	$10.03	0.750
810	5	590	35	0	16	$747	$46.71	$374	$23.35	$0	$0.00	$1,121	$70.06	2.188
810	5	591	337	68	3,665	$10,306	$2.81	$1,036	$0.28	$540	$0.15	$11,882	$3.24	0.111
810	5	594	40	4	105	$1,099	$10.47	$106	$1.00	$352	$3.35	$1,557	$14.83	0.419
810	6	690	454	19	509	$10,343	$20.32	$787	$1.55	$161	$0.32	$11,290	$22.18	0.929
825	2	238	6,593	185	6,778	$143,045	$21.10	$15,170	$2.24	$9,458	$1.40	$167,673	$24.74	1.000
825	3	390	25	30	55	$1,001	$18.19	$27	$0.49	$0	$0.00	$1,027	$18.68	1.000
825	3	391	10	0	10	$243	$24.26	$34	$3.36	$0	$0.00	$276	$27.62	1.000
825	3	392	38	0	38	$660	$17.37	$35	$0.91	$0	$0.00	$695	$18.28	1.000
825	3	393	1,109	0	1,099	$13,712	$12.48	$2,199	$2.00	$0	$0.00	$15,911	$14.48	1.009
825	3	395	504	102	606	$11,605	$19.17	$960	$1.58	$214	$0.35	$12,778	$21.10	1.000
825	4	438	1,916	0	2,986	$42,400	$14.20	$9,964	$3.34	$0	$0.00	$52,364	$17.54	0.642
825	4	491	2	0	2	$48	$23.87	$0	$0.00	$0	$0.00	$48	$23.87	1.000
825	4	496	12	0	12	$262	$21.82	$11	$0.88	$0	$0.00	$272	$22.70	1.000
825	5	591	729	13	741	$18,103	$24.43	$3,154	$4.26	$110	$0.15	$21,367	$28.84	1.000
825	5	593	27	0	27	$482	$17.85	$42	$1.56	$0	$0.00	$524	$19.41	1.000
825	5	594	68	4	72	$1,821	$25.47	$159	$2.23	$0	$0.00	$1,980	$27.70	1.000
825	6	690	692	51	743	$16,657	$22.41	$1,583	$2.13	$2,279	$3.07	$20,518	$27.61	1.000
825	6	691	1	0	1	$33	$65.90	$0	$0.00	$0	$0.00	$33	$65.90	1.000

Table C17. MMS cost report with detailed unit data for in-house 2006-2007 Fiscal Year (continued)

MMSACTNO	DISTRICT	AREA	REGHRS	SAFHRS	UNITS	LABOR $	LAB$/UNIT	EQUIP $	EQP$/UNIT	MAT $	MAT$/UNIT	TOTAL $	$/UNIT	MH/UNIT
845	2	238	9,692	203	9,895	$206,492	$20.87	$25,449	$2.57	$39,188	$3.96	$271,129	$27.40	1.000
845	3	390	173	11	184	$5,035	$27.44	$365	$1.99	$0	$0.00	$5,400	$29.43	1.000
845	3	391	65	0	65	$1,806	$27.79	$336	$5.17	$0	$0.00	$2,143	$32.96	1.000
845	3	392	995	443	1,438	$21,127	$14.70	$3,132	$2.18	$0	$0.00	$24,259	$16.88	1.000
845	3	393	36	0	36	$792	$21.84	$180	$4.96	$0	$0.00	$971	$26.80	1.000
845	3	395	762	40	802	$15,365	$19.17	$1,988	$2.48	$6,270	$7.82	$23,623	$29.47	1.000
845	4	438	164	0	164	$3,507	$21.39	$435	$2.65	$0	$0.00	$3,942	$24.04	1.000
845	4	490	813	2	815	$18,044	$22.15	$2,861	$3.51	$0	$0.00	$20,905	$25.66	1.000
845	4	491	866	3	869	$16,007	$18.42	$1,712	$1.97	$0	$0.00	$17,719	$20.39	1.000
845	4	496	42	0	42	$743	$17.70	$133	$3.17	$0	$0.00	$876	$20.87	1.000
845	5	590	71	0	73	$1,480	$20.34	$288	$3.95	$0	$0.00	$1,767	$24.29	0.973
845	5	591	712	80	792	$20,110	$25.39	$2,324	$2.93	$532	$0.67	$22,966	$29.00	1.000
845	5	592	106	14	120	$1,691	$14.15	$605	$5.06	$0	$0.00	$2,296	$19.22	1.000
845	5	593	394	1	394	$7,647	$19.40	$1,000	$2.54	$11,830	$30.01	$20,477	$51.94	1.000
845	5	594	589	104	693	$15,133	$21.85	$1,550	$2.24	$0	$0.00	$16,683	$24.09	1.000
845	6	690	2,710	185	2,895	$68,040	$23.50	$6,120	$2.11	$2,340	$0.81	$76,500	$26.43	1.000
845	6	691	21	0	21	$504	$23.99	$33	$1.55	$0	$0.00	$536	$25.54	1.000
845	6	692	1	0	1	$20	$39.00	$20	$39.44	$0	$0.00	$39	$78.44	1.000
845	7	799	89	0	89	$1,953	$22.07	$353	$3.99	$0	$0.00	$2,306	$26.06	1.000
845	7	7	89	0	89	$1,953	$22.07	$353	$3.99	$0	$0.00	$2,306	$26.06	1.000
859	1	190	1,176	22	1,198	$24,863	$20.75	$22,436	$18.73	$0	$0.00	$47,299	$39.48	1.000
859	2	238	1,654	0	1,654	$37,570	$22.72	$7,282	$4.40	$982	$0.59	$45,834	$27.72	1.000
859	3	390	12	0	12	$423	$35.26	$12	$0.96	$0	$0.00	$435	$36.22	1.000
859	3	391	19	0	19	$478	$25.83	$72	$3.90	$0	$0.00	$550	$29.73	1.000
859	3	392	42	0	42	$452	$10.88	$31	$0.74	$0	$0.00	$482	$11.62	1.000
859	3	395	217	9	226	$4,303	$19.04	$310	$1.37	$0	$0.00	$4,613	$20.41	1.000
859	4	490	89	0	89	$1,945	$21.86	$152	$1.71	$0	$0.00	$2,098	$23.57	1.000
859	5	590	57	0	57	$1,130	$20.01	$119	$2.11	$0	$0.00	$1,250	$22.12	1.000
859	5	591	195	0	195	$4,016	$20.65	$463	$2.38	$19	$0.10	$4,498	$23.12	1.000
859	5	592	23	3	26	$552	$21.64	$509	$19.97	$0	$0.00	$1,061	$41.61	1.000
859	5	593	11	0	11	$193	$17.53	$58	$5.29	$0	$0.00	$251	$22.82	1.000
859	5	594	71	0	71	$1,605	$22.77	$348	$4.93	$0	$0.00	$1,953	$27.70	1.000
859	5	595	12	0	12	$266	$22.20	$14	$1.13	$0	$0.00	$280	$23.33	1.000
859	6	690	183	0	183	$4,178	$22.80	$759	$4.14	$27	$0.15	$4,964	$27.09	1.000
861	2	238	6,413	0	6,413	$168,310	$26.25	$21,575	$3.36	$10,943	$1.71	$200,828	$31.32	1.000
861	3	390	1	0	1	$62	$62.47	$0	$0.00	$0	$0.00	$62	$62.47	1.000
861	3	391	215	0	215	$5,796	$27.02	$1,062	$4.95	$0	$0.00	$6,859	$31.98	1.000
861	3	395	546	0	546	$15,015	$27.50	$4,429	$8.11	$549	$1.01	$19,993	$36.62	1.000
861	4	490	79	0	79	$1,906	$24.13	$137	$1.74	$0	$0.00	$2,044	$25.87	1.000
861	5	591	46	0	46	$1,192	$25.91	$313	$6.81	$19	$0.41	$1,524	$33.13	1.000
861	5	594	3	1	3	$80	$26.65	$12	$3.92	$0	$0.00	$92	$30.57	1.000
861	6	690	856	32	888	$20,838	$23.47	$2,999	$3.38	$6,703	$7.55	$30,540	$34.39	1.000
865	2	238	3,242	0	3,242	$85,599	$26.41	$10,806	$3.33	$12,524	$3.86	$108,929	$33.60	1.000
865	4	491	94	0	94	$2,209	$23.62	$33	$0.35	$0	$0.00	$2,241	$23.97	1.000
865	6	690	15	0	15	$384	$26.50	$17	$1.17	$59	$4.09	$460	$31.76	1.000
869	2	238	82	0	82	$1,586	$19.34	$178	$2.18	$0	$0.00	$1,764	$21.51	1.000
869	4	438	327	0	443	$7,016	$15.84	$562	$1.27	$0	$0.00	$7,578	$17.11	0.737
869	4	490	18	0	18	$419	$23.29	$91	$5.06	$0	$0.00	$510	$28.36	1.000
869	6	690	138	8	146	$3,024	$20.75	$220	$1.51	$0	$0.00	$3,244	$22.26	1.000
888	4	496	841	0	841	$11,694	$13.91	$1,420	$1.69	$1,385	$1.65	$14,499	$17.24	1.000
888	6	690	186	0	186	$4,415	$23.80	$510	$2.75	$879	$4.74	$5,804	$31.29	1.000
898	4	491	31	0	31	$688	$22.54	$0	$0.00	$0	$0.00	$688	$22.54	1.000
996	1	190	9,835	55	9,995	$209,324	$20.94	$81,305	$8.13	$5,072	$0.51	$295,701	$29.59	0.989
996	1	191	8,944	22	8,967	$183,014	$20.41	$65,441	$7.30	$4,147	$0.46	$252,601	$28.17	1.000
996	1	192	3,537	40	3,603	$51,938	$14.41	$43,127	$11.97	$2,366	$0.66	$97,430	$27.04	0.993
996	1	193	1,501	18	1,519	$15,711	$10.35	$17,161	$11.30	$532	$0.35	$33,404	$22.00	1.000
996	1	194	1,782	17	1,799	$31,123	$17.30	$6,422	$3.57	$0	$0.00	$37,545	$20.87	1.000
996	1	195	8,857	0	8,889	$162,408	$18.27	$60,698	$6.83	$322	$0.04	$223,427	$25.14	0.996
996	2	291	13,419	52	13,485	$267,610	$19.85	$164,962	$12.23	$31,836	$2.36	$464,407	$34.44	0.999
996	2	292	7,402	20	7,402	$187,976	$25.40	$82,950	$11.21	$3,644	$0.49	$274,570	$37.10	1.003
996	2	293	149	8	157	$3,567	$22.72	$782	$4.98	$0	$0.00	$4,349	$27.70	1.000
996	2	294	590	12	602	$17,567	$29.17	$3,481	$5.78	$0	$0.00	$21,048	$34.95	1.000
996	2	297	366	2	368	$7,717	$21.00	$1,190	$3.24	$0	$0.00	$8,907	$24.24	1.000
996	3	390	1,547	0	1,547	$41,927	$27.10	$18,642	$12.05	$0	$0.00	$60,569	$39.15	1.000
996	3	391	1,706	0	1,706	$47,798	$28.03	$26,024	$15.26	$0	$0.00	$73,822	$43.28	1.000
996	3	392	1,759	0	1,759	$34,566	$19.66	$27,506	$15.64	$0	$0.00	$62,072	$35.30	1.000
996	3	393	1,954	0	1,954	$41,269	$21.12	$16,354	$8.37	$0	$0.00	$57,623	$29.49	1.000
996	3	395	309	0	342	$9,127	$26.69	$15,316	$44.78	$0	$0.00	$24,443	$71.47	0.902
996	4	438	586	0	586	$13,121	$22.39	$1,544	$2.63	$0	$0.00	$14,664	$25.02	1.000
996	4	490	24,807	16	24,833	$550,491	$22.17	$155,861	$6.28	$14,579	$0.59	$720,930	$29.03	1.000
996	4	491	14,589	113	14,742	$339,888	$23.06	$77,974	$5.29	$523	$0.04	$418,385	$28.38	0.997
996	4	496	3,282	5	3,287	$58,529	$17.80	$17,671	$5.38	$990	$0.30	$77,190	$23.48	1.000
996	5	590	544	0	545	$10,160	$18.66	$2,598	$4.77	$2,304	$4.23	$15,063	$27.66	0.998

Appendix D: Results from Accident Cost Models

This section describes some of the results from the research effort on the development of accident cost models.

Table D1. Statistical test on approach alignment ratings

```
Two-sample T for “Bad” Appralign vs “Good” Appralign

                   N  Mean  StDev  SE Mean
Bad Appralign    254   140    599       38
Good Appralign  5181    68    198      2.8

Difference = mu (Bad Appralign) - mu (Good Appralign)
Estimate for difference:  72.0
90% CI for difference:  (9.8, 134.2)
T-Test of difference = 0 (vs not =): T-Value = 1.91  P-Value = 0.057  DF = 255
```

Table D2. Statistical Test on Deck Ratings

```
Two-sample T for “Bad” Deck vs “Good” Deck

              N  Mean  StDev  SE Mean
Bad Deck    617    86    137      5.5
Good Deck  4818    70    243      3.5

Difference = mu (Bad Deck) - mu (Good Deck)
Estimate for difference:  16.22
95% CI for difference:  (3.44, 29.00)
T-Test of difference = 0 (vs not =): T-Value = 2.49  P-Value = 0.013  DF = 1189
```

Table D3. Correlation analysis output prior to logistic regression

```
    (obs=21684)

                 | speedmph aroadw~h roadwi~h   funnel funnel_m funnel~2 relati~h sumlanes narrow~s
curbsw
    -------------+---------------------------------------------------------------------------------
------
        speedmph |   1.0000
      aroadwidth |   0.0808   1.0000
       roadwidth |   0.0780   0.9467   1.0000
          funnel |  -0.0206   0.2524  -0.0375   1.0000
        funnel_m |  -0.0328   0.0654  -0.0815   0.5251   1.0000
       funnel_m2 |   0.1018  -0.2527  -0.1793  -0.2143   0.3475   1.0000
    relativewi~h |   0.0108   0.1896  -0.1367   0.8907   0.4499  -0.2305   1.0000
        sumlanes |  -0.0199   0.8897   0.9109   0.0565  -0.0256  -0.1978  -0.0405   1.0000
      narrowness |  -0.2056   0.0843   0.0144   0.2801   0.1799  -0.0652   0.2153   0.3853   1.0000
          curbsw |  -0.3979   0.1686   0.1716   0.0645   0.0098  -0.0976  -0.0045   0.3070   0.3548
1.0000
        lengthmi |  -0.0552  -0.0191  -0.0306   0.0376   0.0335  -0.0235   0.0345  -0.0342  -0.0177  -
0.0115
             adt |   0.1674   0.6750   0.6517   0.1305   0.0054  -0.2199   0.0895   0.6577   0.1354  -
0.0153
        truckpct |   0.4099  -0.1928  -0.1648  -0.1082  -0.0451   0.1623  -0.0906  -0.2063  -0.1348  -
0.1803
       funcclass |  -0.4759   0.2447   0.2229   0.1182   0.0267  -0.1892   0.0731   0.2743   0.1689
0.2898
     funcclass_m |  -0.2535   0.2496   0.2419   0.0690  -0.0332  -0.1974   0.0304   0.3053   0.1736
0.2351
        dkrating |   0.0189   0.0382   0.0732  -0.1029  -0.1291  -0.0473  -0.1058   0.0104  -0.1690  -
0.0549
      dkrating_m |  -0.0469   0.0049  -0.0119   0.0551   0.0455  -0.0321   0.0515   0.0190   0.0965
0.0478
       appralign |   0.3333   0.0649   0.0934  -0.0924  -0.0906   0.0378  -0.0851   0.0708  -0.0168  -
0.0654
     appralign_m |  -0.3329  -0.0702  -0.1046   0.1138   0.0785  -0.0660   0.1031  -0.0806   0.0125
0.1000
       frequency |  -0.0554   0.3984   0.3825   0.0862   0.0114  -0.1771   0.0592   0.4614   0.2393
0.1496
            risk |  -0.1460   0.0751   0.0653   0.0425   0.0179  -0.0779   0.0320   0.1287   0.1442
0.1460
             log |  -0.0339   0.3148   0.2941   0.1024   0.0263  -0.1466   0.0716   0.3421   0.1792
0.1433
           logit |   0.0397   0.3583   0.3369   0.1072   0.0237  -0.1465   0.0750   0.3660   0.1496
0.1049

                 | lengthmi      adt truckpct funccl~s funccl~m dkrating dkrati~m appral~n appral~m
freque~y
    -------------+---------------------------------------------------------------------------------
------
        lengthmi |   1.0000
             adt |  -0.0101   1.0000
        truckpct |  -0.0565  -0.2141   1.0000
       funcclass |   0.0477   0.2260  -0.5431   1.0000
     funcclass_m |   0.0679   0.3106  -0.2639   0.5853   1.0000
        dkrating |  -0.0829  -0.0276  -0.0008  -0.0031  -0.0350   1.0000
      dkrating_m |   0.0798   0.0605  -0.0340   0.0549   0.0674  -0.5355   1.0000
       appralign |  -0.0946   0.0354   0.1546  -0.1788  -0.0626   0.0226  -0.0374   1.0000
     appralign_m |   0.0383  -0.0633  -0.1304   0.1549   0.0428   0.0014   0.0105  -0.7642   1.0000
       frequency |   0.1180   0.5305  -0.1814   0.1868   0.2371  -0.0164   0.0568  -0.0254   0.0297
1.0000
            risk |   0.1022   0.0326  -0.0899   0.1126   0.1386   0.0099   0.0243  -0.0725   0.0721
0.5175
             log |   0.1228   0.3484  -0.1458   0.2198   0.2902  -0.0707   0.0695  -0.0306   0.0149
0.5345
           logit |   0.0849   0.4211  -0.1430   0.2162   0.2917  -0.0786   0.0683  -0.0003  -0.0210
0.4232

                 |     risk      log    logit
    -------------+---------------------------
            risk |   1.0000
             log |   0.5110   1.0000
           logit |   0.3535   0.9590   1.0000
```

Table D4. Stepwise regression analysis output prior to logistic regression

```
                     begin with full model
p = 0.1554 >= 0.1000  removing appralign_m
p = 0.1420 >= 0.1000  removing relativewidth

      Source |       SS       df       MS              Number of obs =   21684
-------------+------------------------------           F(  9, 21674) =  718.42
       Model |  1245.59331     9  138.399257           Prob > F      =  0.0000
    Residual |  4175.37786 21674  .192644545           R-squared     =  0.2298
-------------+------------------------------           Adj R-squared =  0.2295
       Total |  5420.97118 21683    .2500102           Root MSE      =  .43891

------------------------------------------------------------------------------
       logit |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
    speedmph |    .002938    .000291    10.09   0.000     .0023675    .0035085
      funnel |   .1262142   .0200742     6.29   0.000     .0868672    .1655611
   dkrating_m |    .087709    .018909     4.64   0.000     .0506461     .124772
    sumlanes |   .0345491   .0029699    11.63   0.000     .0287277    .0403704
  narrowness |   .2969139   .0854487     3.47   0.001     .1294282    .4643995
      curbsw |   .0173115    .002334     7.42   0.000     .0127368    .0218863
    lengthmi |   .1709632   .0126192    13.55   0.000     .1462287    .1956977
         adt |   4.26e-06   1.35e-07    31.62   0.000     4.00e-06    4.52e-06
 funcclass_m |    .165526   .0068518    24.16   0.000     .1520959     .178956
       _cons |  -.1515645   .0270072    -5.61   0.000    -.2045005   -.0986284
------------------------------------------------------------------------------
```

Table D5. Logistic regression analysis output: odds ratio

```
Logistic regression                               Number of obs   =      21684
                                                  LR chi2(9)      =    6787.89
                                                  Prob > chi2     =     0.0000
Log likelihood = -11636.199                       Pseudo R2       =     0.2258
------------------------------------------------------------------------------
       logit | Odds Ratio   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
    sumlanes |   1.194854   .0220023     9.67   0.000     1.152499    1.238766
         adt |   1.000044   1.19e-06    37.23   0.000     1.000042    1.000047
 funcclass_m |   1.876279   .0683119    17.28   0.000     1.747056    2.015061
    lengthmi |   3.465159   .3573412    12.05   0.000     2.831026    4.241334
      funnel |    1.22845   .1309086     1.93   0.054      .996896    1.513787
    speedmph |   1.006535   .0015778     4.16   0.000     1.003448    1.009633
      curbsw |   1.031381   .0129551     2.46   0.014       1.0063    1.057088
  dkrating_m |    1.59828   .1731687     4.33   0.000     1.292491    1.976414
  narrowness |   19.86199   9.629783     6.16   0.000     7.679464    51.37062
------------------------------------------------------------------------------
```

Table D6. Poisson regression output for model 1.

❖ Model 1

```
. poisson  frequency speed sumlanes curbsw lengthmi adt2 fc_m
Poisson regression                                Number of obs   =      21684
                                                  LR chi2(6)      =   64810.42
                                                  Prob > chi2     =     0.0000
Log likelihood = -64215.981                       Pseudo R2       =     0.3354
------------------------------------------------------------------------------
   frequency |      Coef.   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
       speed |  -.0113098   .0004415   -25.62   0.000    -.0121752   -.0104445
    sumlanes |   .1086604   .0027075    40.13   0.000     .1033539    .1139669
      curbsw |   .1110656   .0024344    45.62   0.000     .1062943    .1158369
    lengthmi |   .5727457   .0073412    78.02   0.000     .5583573    .5871342
        adt2 |   .0000129   1.16e-07   111.02   0.000     .0000127    .0000131
        fc_m |   .4436262   .0096394    46.02   0.000     .4247334     .462519
       _cons |   .3004421   .0261104    11.51   0.000     .2492667    .3516175
------------------------------------------------------------------------------
. estat gof
         Goodness-of-fit chi2  =  95637.24
         Prob > chi2(21677)    =    0.0000
```

Table D7. Poisson regression output for model 2

❖ Model 2

```
. poisson  frequency speed sumlanes narrowness lengthmi adt2 fc_m age ctime
Poisson regression                                Number of obs   =      21684
                                                  LR chi2(8)      =   93359.05
                                                  Prob > chi2     =     0.0000
Log likelihood = -49941.663                       Pseudo R2       =     0.4831
------------------------------------------------------------------------------
   frequency |      Coef.   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
       speed |  -.0179876   .0004234   -42.49   0.000    -.0188174   -.0171578
    sumlanes |   .0758768    .002666    28.46   0.000     .0706516     .081102
  narrowness |   2.516247   .0727989    34.56   0.000     2.373564     2.65893
    lengthmi |   .4860147   .0075347    64.50   0.000      .471247    .5007825
        adt2 |   .0000113   1.10e-07   103.21   0.000     .0000111    .0000115
        fc_m |   .1786433   .0094761    18.85   0.000     .1600705    .1972161
         age |   .0160287   .0002894    55.38   0.000     .0154615     .016596
       ctime |   2.249024   .0217965   103.18   0.000     2.206304    2.291744
       _cons |   -.781565   .0312003   -25.05   0.000    -.8427164   -.7204135
------------------------------------------------------------------------------
. estat gof
         Goodness-of-fit chi2  =  67088.61
         Prob > chi2(21675)    =    0.0000
```

Table D8. Poisson regression output for model 3

- Model 3

```
. poisson  frequency speedmph aroadwidth funnel relativewidth sumlanes
narrowness curbsw lengthmi adt fc_m dkrating_m
Poisson regression                                Number of obs   =      21684
                                                  LR chi2(11)     =   66674.99
                                                  Prob > chi2     =     0.0000
Log likelihood = -63283.696                       Pseudo R2       =     0.3450
------------------------------------------------------------------------------
   frequency |      Coef.   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
    speedmph |  -.0082851   .0004496   -18.43   0.000    -.0091663   -.0074038
  aroadwidth |   .0315115   .0018623    16.92   0.000     .0278615    .0351614
      funnel |   .1301254   .0493279     2.64   0.008     .0334446    .2268063
relativewi~h |  -.0206065   .0029711    -6.94   0.000    -.0264298   -.0147833
    sumlanes |  -.0629602   .0093891    -6.71   0.000    -.0813625   -.0445578
  narrowness |   5.262584   .1660435    31.69   0.000     4.937144    5.588023
      curbsw |   .1003305   .0024812    40.44   0.000     .0954674    .1051937
    lengthmi |   .5669815   .0073593    77.04   0.000     .5525577    .5814054
         adt |   .0000119   1.12e-07   106.65   0.000     .0000117    .0000122
        fc_m |   .4335742   .0096803    44.79   0.000     .4146011    .4525473
  dkrating_m |    .042421   .0196981     2.15   0.031     .0038134    .0810286
       _cons |  -.9466258   .0550231   -17.20   0.000    -1.054469   -.8387824
------------------------------------------------------------------------------
. estat gof
         Goodness-of-fit chi2  =  93772.67
         Prob > chi2(21672)    =    0.0000
```

Table D9. Frequency analyses for poisson and negative binomial probabilities

```
. nbvargr frequency

Obtaining Parameter Estimates

(64 observations deleted)                    (0 observations deleted)
Negative Binomial Probabilities               Poisson Probabilities
with mean = 2.767017 &                        for lambda = 2.767017
overdispersion = 3.573311

 k       nbprob       nbcum                 k        pprob        pcum
  0  0.51264183  0.51264185                 0  0.06284920  0.06284920
  1  0.13028704  0.64292890                 1  0.17390482  0.23675403
  2  0.07571625  0.71864510                 2  0.24059880  0.47735283
  3  0.05225557  0.77090067                 3  0.22191365  0.69926649
  4  0.03891212  0.80981278                 4  0.15350971  0.85277617
  5  0.03024835  0.84006113                 5  0.08495279  0.93772900
  6  0.02417298  0.86423415                 6  0.03917764  0.97690660
  7  0.01969425  0.88392836                 7  0.01548646  0.99239308
  8  0.01627534  0.90020370                 8  0.00535641  0.99774945
  9  0.01359778  0.91380149                 9  0.00164681  0.99939626
 10  0.01145954  0.92526102                10  0.00045567  0.99985194
```