JOINT TRANSPORTATION
RESEARCH PROGRAM
INDIANA DEPARTMENT OF TRANSPORTATION
AND PURDUE UNIVERSITY

Economic Development Impact of Preservation Projects

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SPR-3912• Report Number: FHWA/IN/JTRP-2019/05 • DOI: 10.5703/1288284316882

RECOMMENDED CITATION

Ke, Y., Losada-Rojas, L. L., Chacon-Hurtado, D., Khair, S., Gkritza, K., & Fricker, J. D. (2019). *Economic development impact of preservation projects* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2019/05). West Lafayette, IN: Purdue University. https://doi.org/10.5703/1288284316882

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TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. FHWA/IN/JTRP-2019/05	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle Economic Development Impact of Preservation Projects		**5. Report Date** February 2019 **6. Performing Organization Code**
7. Author(s) Yue Ke, Lisa Lorena Losada-Rojas, Davis Chacon-Hurtado, Sumedh Khair, Konstantina Gkritza, and Jon D. Fricker		**8. Performing Organization Report No.** FHWA/IN/JTRP-2019/05
9. Performing Organization Name and Address Joint Transportation Research Program Hall for Discovery and Learning Research (DLR), Suite 204 207 S. Martin Jischke Drive West Lafayette, IN 47907		**10. Work Unit No.** **11. Contract or Grant No.** SPR-3912
12. Sponsoring Agency Name and Address Indiana Department of Transportation (SPR) State Office Building 100 North Senate Avenue Indianapolis, IN 46204		**13. Type of Report and Period Covered** Final Report **14. Sponsoring Agency Code**
15. Supplementary Notes Conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.		

16. Abstract

Preservation and maintenance activities protect pavements and bridges, extending the life of these assets and guarantee the safety of users. Because rebuilding a road in poor condition can cost ten times as much as work needed to keep the road in good condition, these activities also represent significant savings to taxpayers. In addition to these benefits, preservation activities can also have wider economic benefits in the form of reduced user costs related to vehicle operation, travel time, and safety.

This project aims to develop sketch planning tools for assessing the economic development impacts of pavement and bridge preservation projects to meet the needs of INDOT's Division of Asset Planning and Management. To accomplish these objectives, the following tasks were undertaken: a literature review, an evaluation of existing tools that could address some aspect of the study topic or be used as guidance for the development of the project tools, the development of the tool, and the preparation of guidance materials and documentation.

17. Key Words economic development, pavement preservation, bridge preservation		**18. Distribution Statement** No restrictions. This document is available through the National Technical Information Service, Springfield, VA 22161.	
19. Security Classif. (of this report) Unclassified	**20. Security Classif. (of this page)** Unclassified	**21. No. of Pages** 45	**22. Price**

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

EXECUTIVE SUMMARY

ECONOMIC DEVELOPMENT IMPACT OF PRESERVATION PROJECTS

Introduction

Preservation and maintenance activities protect pavements and bridges, extending the life of these assets and guaranteeing the safety of users. While preservation and maintenance work have significant overlap, some key differences exist. Preservation is work that is planned and performed to improve or keep a facility in a state of good repair. Usually, these activities do not add capacity or structural value but return the highway to an almost new condition or help keep it that way. Maintenance is work performed to sustain the condition of the facility or to respond to specific conditions or events to restore the highway to functional operation. Because rebuilding a road in poor condition can cost ten times as much as the work needed to keep the road in good condition, these activities also represent significant savings to taxpayers. In addition to these benefits, preservation activities can also have wider economic benefits in the form of reduced user costs related to vehicle operation, travel time, and safety.

This study aims to develop sketch-planning tools for assessing the economic impacts of pavement and bridge preservation projects to meet the needs of INDOT's Division of Asset Planning and Management. To accomplish these objectives, the following tasks were undertaken: (1) a literature review, (2) an evaluation of existing tools that could address some aspect of the study topic or be used as guidance for the development of the project tools, (3) the development of the tool, and (4) the preparation of guidance materials and documentation.

Findings

Following the work of the preceding phase of SPR-3912, which involved the development of a framework to study the economic impacts of corridor improvements, this work adapts the previous framework to account for pavement and bridge preservation interventions. While the specific preservation treatment is not accounted for (because that was beyond the scope of this study), the framework accounts for treatment via changes in conditions as measured in International Roughness Index (IRI) for pavements and in load capacity limits due to structural deficiencies of bridges.

The approach adopted to evaluate the economic impacts of non-capacity transportation projects involved estimating the impacts of changes in pavement and bridge deck conditions on key performance measures. These include vehicle operating costs, travel time costs, and safety outcomes. The key indicators were translated into business cost savings and then into economic impacts through statewide economic multipliers.

Based on the theoretical framework, literature review findings, and existing tools for similar analysis, several different tool development options were considered. From among them, a framework jointly based on Highway Economic Requirements System—State Version (HERS-ST) and Tool for Operations—Economic Impact Analysis (TOPS-EIA) was chosen. The resulting Pavement and Bridge Preservation—Economic Impact Analysis (EIA) tools are briefly described in the following section.

Pavement and Bridge Preservation EIA Tools

EIA tools are intended to be used at the initial stages of the project development process, where various pavement and bridge preservation project alternatives can be analyzed with a low level of detail. In that sense, these tools calculate the user cost savings in travel time, vehicle operating costs, and safety by mode and trip purpose, using a set of expected impacts adopted from past studies and projects. Similarly, the annual business savings corresponding to trucks and automobiles on work-related purposes are converted into economic impacts through the use of economic multipliers from MCIBAS-SEAT (Major Corridor Investment Benefit Analysis System—Simplified Economic Analysis Tool).

The main inputs of the pavement tool include the first and second conditions of the road, as measured in IRI. The bridge tool asks for inputs on the live load limit for bridges, [detour] length of the segment, the average effective speed of vehicles, and the volume of vehicles for the segment under analysis. The outputs of the tools include three types of economic impacts, measured at the state level: gross regional product (GRP) in millions of dollars, personal income in millions of dollars, and employment in job-years.

Implementation

The Pavement and Bridge Preservation EIA tools can be used for screening projects' impacts, project prioritization, or as part of multi-criteria analysis (MCA). Similarly, intermediate outputs of the tool, such as user benefits (e.g., travel time savings), can be used as part of a benefit-cost analysis (BCA). However, the latter will require the calculation of project costs, which these tools do not perform. For MCA, indicators such as GRP, personal income, employment, and any of the intermediate outputs generated by the tool can be incorporated directly as criteria in the decision-making process. The main advantage of MCA is that it accounts for strengths of other criteria, which can make up for deficiencies in any one criterion. However, it is still possible to double-count benefits with MCA. Furthermore, as part of this study, a set of training sessions, webinars, and presentations will be provided for INDOT and metropolitan planning organizations (MPOs). These sessions will cover both the theoretical background as well as a case study to demonstrate the use of the tools in action.

CONTENTS

1. INTRODUCTION . . . 1
1.1 Overview . . . 1
1.2 Organization of the Report . . . 1

2. LITERATURE REVIEW . . . 1
2.1 Overview of Preservation Treatments . . . 1
2.2 Economic Impacts . . . 2
2.3 Estimation of User Costs . . . 7

3. PAVEMENT PRESERVATION EIA TOOL . . . 9
3.1 Evaluation of Existing Tools . . . 9
3.2 Tool Development . . . 10
3.3 Demonstration of Tool . . . 13

4. BRIDGE PRESERVATION EIA TOOL . . . 16
4.1 Evaluation of Existing Tools . . . 16
4.2 Bridge Preservation (BP) EIA Tool . . . 19
4.3 Demonstration of the BP-EIA Tool . . . 21

5. CONCLUSIONS . . . 24
5.1 Summary of PP-EIA and BP-EIA Tools . . . 24
5.2 Applicability and Limitations of PP-EIA and BP-EIA Tools . . . 25
5.3 Implementation Plan . . . 25

REFERENCES . . . 25

APPENDICES
Appendix A: Voc Module Equations and Simplifying Assumptions . . . 27
Appendix B: Safety Module Equations and Simplifying Assumptions . . . 30
Appendix C: Additional Truck Weight Histograms (Volumes from Synthetic Week) . . . 32
Appendix D: Unit Conversions . . . 37

LIST OF TABLES

Table	Page
Table 2.1 INDOT Pavement Preservation Treatments	3
Table 2.2 INDOT Flexible Pavement Maintenance Treatment Guidelines	3
Table 2.3 INDOT Rigid Pavement Preventive Maintenance Treatment Guidelines	4
Table 2.4 Preventative Maintenance Activities for Bridges	4
Table 3.1 HERS and FHWA Vehicle Classification Schema	11
Table 3.2 HERS and FHWA Roadway Classification Systems	15
Table D.1 Table of Unit Conversions	37

LIST OF FIGURES

Figure	Page
Figure 2.1 Categories of economic impacts	5
Figure 2.2 Existing tools for the evaluation of transportation projects	6
Figure 3.1 Framework of PP-EIA tool	10
Figure 3.2 AADT to vehicle count framework	12
Figure 3.3 Pavement VOC example—user inputs	13
Figure 3.4 Pavement VOC module example—results	14
Figure 3.5 Pavement travel time module example	14
Figure 3.6 Pavement safety module example—user inputs	15
Figure 3.7 Pavement safety module example—results	15
Figure 3.8 Pavement economic impacts analysis module example	16
Figure 4.1 Framework of bridge tool	19
Figure 4.2 Truck weight distribution (all classes; in kips)	20
Figure 4.3 Bridge VOC module example	22
Figure 4.4 Bridge travel time module example	23
Figure 4.5 Bridge economic impacts analysis module example	24
Figure C.1 Class 5 trucks	32
Figure C.2 Class 6 trucks	32
Figure C.3 Class 7 trucks	33
Figure C.4 Class 8 trucks	33
Figure C.5 Class 9 trucks	34
Figure C.6 Class 10 trucks	34
Figure C.7 Class 11 trucks	35
Figure C.8 Class 12 trucks	35
Figure C.9 Class 13 trucks	36

1. INTRODUCTION

1.1 Overview

Preservation and maintenance activities preserve and protect pavements and bridges, extending the life of these assets, and guaranteeing the safety of users (INDOT, 2017). These activities represent significant savings to taxpayers, because rebuilding a road that is in poor condition can cost ten times as much the work needed to keep the road in good condition (INDOT, 2017). The Indiana Department of Transportation (INDOT) protects its investments with pavement and bridge preservation. Pavement preservation is a practical approach to maintain existing pavements and reduce expensive and time-consuming rehabilitation and reconstruction projects (Lee & Shields, 2011). In a similar way, bridge preservation activities help prevent, mitigate and delay the deterioration of these assets. The main benefits of bridge preservation include an increase in the percentage of bridges with a condition rating of fair or better. Nevertheless, it is important to understand the economic benefits of preservation activities, which are mainly seen in the reduction of user costs related to vehicle operation, travel time, and safety.

The objectives of this study are to:

1. Develop a sketch-planning tool for assessing the economic impacts of pavement and bridge preservation projects.
2. Customize the developed tool in order to meet the needs of INDOT's Division of Asset Planning and Management.

The deliverables of this study will be used by INDOT for middle-stage transportation sketch-planning that involves single projects and/or for transportation programming. To this end, these specific tasks were undertaken:

1. *Literature review*: A synthesis was conducted of existing work on highway capacity, operational and preservation improvements, and economic development that has been published in transportation engineering, policy, and planning journals, or published in agency reports. This synthesis yielded established relationships for the anticipated economic impacts of highway capacity, operational, and preservation projects.
2. *Evaluation of candidate tools*: Based on Task 1, the existing tools as well as the best practices in assessing the economic development impact of capacity, operational, and preservation improvements were identified. This task provided a comparison of tools including ISTDM, MCIBAS-SEAT, TOPS B/C, TOPS-EIA, and HERS-ST. Dimensions of comparison included structure and usability (e.g., resources required, level of difficulty), strategies and treatments (e.g., benefit and cost data, relevance of studies considered, missing data), inputs (e.g., default values, consistency across categories), formulas and quantitative relationships included to measure benefits, costs, and economic impacts, and outputs (e.g., benefits, costs, economic impacts).
3. *Tool development*: Based on findings from Tasks 1 and 2, a tool for pavement preservation and a tool for bridge preservation have been developed. The research team examined the feasibility of adapting existing tools for preservation projects.
4. *Tool demonstration* with realistic input values; and
5. *Guidance material and documentation*: The research team has developed guidance material and documentation to support the economic impact analysis of (non-traditional) corridor improvements.

The information provided herein aims to provide the following benefits for INDOT:

- Offer guidance to INDOT about proposed pavement and bridge preservation projects;
- Provide information to support the decision-making process when evaluating projects at the middle-stage transportation sketch planning or during project programming, or the early stages of project development; and
- Assist INDOT with communicating the process to elected officials, the general public, and other stakeholders.

1.2 Organization of the Report

The structure of this report is as follows. Chapter 2 presents an overview of existing work on highway capacity, operational and preservation improvements, and economic development literature. This chapter also presents an overview of available tools that assess the economic impacts of operational improvements and preservation treatments. Chapter 3 provides the description of different tools that estimate costs and benefits associated with preservation projects in pavement assets; a description of the Pavement Preservation—Economic Impact Analysis (PP-EIA) tool including its development framework, main inputs, and outputs; and concludes with a numerical example using realistic inputs showing the tool in practice. Chapter 4 provides the summary of various tools and research examining bridge asset management; a description of the Bridge Preservation—Economic Impact Analysis (BP-EIA) tool including its development framework, main inputs, and outputs; and a numerical example demonstrating the tool in practice. Finally, a summary of the key findings, lessons learned, and opportunities for future research are presented in Chapter 5.

2. LITERATURE REVIEW

This chapter describes the key concepts examined in this study, namely, pavement preservation, economic benefits of preservation projects, and economic impacts of transportation projects. Next, tools for the measurement of user benefits and economic impacts, as well as past related studies, are summarized.

2.1 Overview of Preservation Treatments

The preservation of the existing transportation system is critical to transportation agencies (Ong, Nantung, & Sinha, 2011). A well-connected highway system is crucial to a strong national economy. However, agencies face increasing costs to maintain and preserve their assets. Additionally, state Departments of Transportation (DOTs) have made efforts to develop pavement

preservation programs using quantitative methods to determine which road segments should be prioritized for treatment. In many states, however, these programmatic decisions are primarily based on engineering judgment rather than being empirically determined (Ong et al., 2011). The two main components transportation agencies are concerned with are pavement structures (roads) and bridges. In the case of the INDOT, these two assets are the focus of an initiative that is making investments to preserve and maintain Indiana's existing roads, bridges and infrastructure.

2.1.1 Pavement Preservation

Pavement preservation is a practical approach to maintaining existing pavements. It reduces the need for costly, time-consuming rehabilitation and reconstruction projects. It uses a variety of treatments that range across a spectrum of scope, cost, and effectiveness. Preservation usually refers to planned treatments that are on the low end of this spectrum. They are intended to slow the pavement deterioration or reverse it slightly. They are most effective on roads that are already in good condition. Most pavement management plans focus on keeping good roads in good condition. This allows DOTs to stretch their limited resources and ensures that users get the benefits of a smoother ride. Ideally, the lifespan of a good road can be extended indefinitely by the application of correct treatments in a timely manner. It should also be noted that pavement treatments have a shelf-life. If the selected fix is not implemented in a timely fashion, the pavement may degrade to a point that requires a more extensive and expensive treatment.

Several treatments can be used to preserve an asset. The preservation activities for pavement assets include resurfacing, crack sealing, chip sealing, pothole repair, and storm water drainage maintenance. There are several benefits of pavement preservation, which include greater values of the asset, lower taxpayer cost, improved (visual) appearance, and safety improvements. Preservation can also slow the deterioration of the asset and achieve smoother and safer roads with fewer costly repairs (FHWA, 2016). INDOT released its own treatment guidelines for pavement preservation. Some strategies used for bridge and pavements are found in Table 2.1.

Many state DOTs have developed their own process to select preservation treatments. For instance, INDOT developed a comprehensive list of parameters to consider when selecting preservation treatments for flexible and rigid pavements. Those considerations are presented in Table 2.2 and Table 2.3. For flexible pavements, preventive maintenance treatments are applied to pavements with an international roughness index (IRI) less than 150 in/mi and with low to moderate cracks. For rigid pavements, guidelines based on IRI or friction, are not stated in the INDOT documentation.

Finally, the benefits of pavement preservation can be financial, performance-related, or sustainability-related. For instance, pavement preservation can stabilize the cost of operating and maintaining highway pavements, which is a financial benefit for an agency. Additionally, the right preservation treatment applied to highway pavements can extend the service life of the asset and reduce the need for frequent reconstruction. Last, a well-defined preservation plan can help setting achievable performance targets, which can provide sustainability benefits (FHWA, 2016). However, while benefits can be identified, they are typically not well quantified.

2.1.2 Bridge Preservation

Bridge preservation activities are designed to delay, mitigate, or prevent deterioration of bridge assets. The preservation activities of bridges include cleaning, inspection, bridge deck overlay, and substructure or superstructure repair. Like preservation of pavement assets, the benefits of bridge preservation include maintaining the value of the asset, lowering taxpayer costs, and increasing the percentage of bridges with condition ratings of fair or better. Examples of preventive maintenance activities for bridges are presented in Table 2.4.

2.2 Economic Impacts

2.2.1 Definition

Economic development describes the changes in a community's economy. This can be described by changes in metrics such as increases in employment, personal income, productivity, property values, tax revenues, and gross regional product. Economic development impact types can be classified into two groups (Sinha & Labi, 2007):

- Impact types related to the regional economy, such as economic output, personal income, and employment.
- Impact types related to a particular aspect of economic development, such as productivity, capital investment, and tax revenues.

Economic impacts can interact with each other. An impact can be classified in terms of its effect on the economy such as whether changes are a direct, indirect, or induced result of a given project, program, or policy (Sinha & Labi, 2007). The economic impacts of transportation projects can be further placed into four groups of categories: direct impacts, indirect impacts, induced impacts, and dynamic impacts. An expanded definition for each of these impacts is given in sections 2.2.1.1–2.2.1.4. (Forkenbrock & Weisbrod, 2001). Figure 2.1 illustrates these categories of economic impacts.

2.2.1.1 Direct Economic Impacts. Cost savings resulting from changes in transportation system characteristics (i.e., travel time and safety) and changes in costs (e.g., vehicle operating costs) can enhance business output and increase productivity in a region, thus

TABLE 2.1
INDOT Pavement Preservation Treatments

Strategy	Type of Pavement	Description	Source
Thin hot-mix overlays	Flexible	Improves ride quality, reduces pavement distresses, reduces life-cycle cost, and provides long-lasting service.	(NAPA, 2012)
Crack treatments	Flexible	Higher quality material is placed into cracks to reduce water infiltration. Effective at reducing or delaying moisture damage.	(Bureau of Design and Environment Manual, 2010)
Chip Seals	Flexible	Fills and seals cracks, also provides an anti-glare surface during rainy conditions. Effective in keeping water from penetrating the paved surface.	(WSDOT, 2018)
Fog Seals	Flexible	A very light application of an emulsion placed on the pavement surface with no aggregate. Effective at sealing the pavement.	(Bureau of Design and Environment Manual, 2010)
Slurry seals	Flexible	A mixture of crushed well-graded aggregated and asphalt emulsion spread over the entire pavement surface. Effective at sealing low-severity cracks.	(Bureau of Design and Environment Manual, 2010)
Micro surfacing	Flexible	A process similar to slurry seals. Effective at correcting raveling and oxidation of the pavement surface.	(Bureau of Design and Environment Manual, 2010)
Ultrathin bonded wearing courses	Flexible	An alternative to micro-surfacing, since it addresses minor surface distresses.	(Bureau of Design and Environment Manual, 2010)
Maintenance of drainage features	Flexible and Rigid	Effective in preventing water from remaining in the roadway, which can contribute to hydroplaning or become ice in winter.	(McGee, Nabors, & Baughman, 2009)
Crack and joint sealing	Rigid	Effective at reducing or delaying moisture damage and retards the rate of crack deterioration.	(Bureau of Design and Environment Manual, 2010)
Diamond grinding	Rigid	A removal of a thin layer of concert using special equipment, diamond saw blades. Effective at removing joint faulting and other surface irregularities.	(Bureau of Design and Environment Manual, 2010)
Diamond grooving	Rigid	Reduces hydroplaning by increasing wet-pavement friction and reducing splash and spray in certain areas.	(Bureau of Design and Environment Manual, 2010)
Dowel bar retrofits	Rigid	Restores or provides better load transfer across transverse joints or cracks using dowel bars.	(FHWA, 2018a)
Patching	Rigid	Removal and replacement of unsound concrete to treat localized slab problems such as spalling, scaling, and joint deterioration.	(FHWA, 2018b)
Load transfer restriction	Rigid	Installation of mechanical devices in existing pavement to restore load transfer. Suitable for transverse joints or cracks.	(Smith, 2009)

TABLE 2.2
INDOT Flexible Pavement Maintenance Treatment Guidelines (INDOT, 2017)

Treatment	AADT[1]	Pavement Distress	Rutting (in)	IRI (in/mi)	Friction Treatment?	Surface Aging
Crack seal	Any	Low to moderately severe surface cracks	n/a	n/a	No	n/a
Fog seal	<5000[2]	Low severity environmental cracks	n/a	n/a	No[3]	Reduces aging and oxidation; arrests minor raveling
Seal coat	<5000[2]	Low severity environmental cracks	<0.25[4]	n/a[4]	Yes	Reduces aging and oxidation; arrests minor raveling
Micro-surfacing	Any	Low severity surface cracks	Any	<130	Yes	Reduces aging and oxidation; arrests minor raveling
Ultra-bond white coating	Any	Low to moderately severe surface cracks	<0.25[4]	<140	Yes	Reduces aging and oxidation; arrests moderate raveling
HMA inlay	Any	Low to moderately severe surface cracks	Any	<150	Yes	Reduces aging, oxidation, and raveling
HMA overlay	Any	Low to moderately severe surface cracks	Any	<150	Yes	Reduces aging, oxidation, and moderate raveling

[1]For mainline pavement.
[2]Unless traffic can be adequately controlled.
[3]Treatment may reduce skid numbers.
[4]Treatment does not address this.

TABLE 2.3
INDOT Rigid Pavement Preventive Maintenance Treatment Guidelines (INDOT, 2017)

Treatment	AADT[1]	Pavement Distress	IRI (in/mi)	Friction Treatment?	Surface Aging
Crack seal	Any	Mid-panel cracks with aggregate interlock	n/a	No	n/a
Saw and seal joints	Any	>10% joints with missing sealant; otherwise joints in good condition	n/a	No	n/a
Retrofit load transfer	Any	Low to medium severity mid-panel cracks; pumping or faulting at joints <0.25 in	n/a	No	n/a
Surface profiling	Any	Faulting <0.25 in.; poor road; friction problems	n/a	No	n/a
Partial depth patch	Any	Localized surface deterioration	n/a	Yes	n/a
Full depth patch	Any	Deteriorated joints; faulting > 0.25 in.; cracks	n/a	No	n/a
Underseal	Any	Pumping; voids under pavement	n/a	No	n/a
Slab jacking	Any	Settled slabs	n/a	No	n/a

[1]For mainline pavement.

TABLE 2.4
Preventative Maintenance Activities for Bridges

Strategy	Description	Source
Bridge washing and or cleaning	Applied to deck and/or super/substructure, to decrease the deterioration cause by debris, bird droppings, and contaminants.	(U.S. Department of Transportation, 2018)
Sealing deck joints	Protects the reinforcing steel from corrosion by stopping or minimizing the intrusion of liquids through the concrete.	(U.S. Department of Transportation, 2018)
Facilitating drainage	Removes litter and other materials from the drainage system.	(Bowman & Moran, 2017)
Sealing concrete	Seals the deck surface to protect reinforcing steel from corrosion.	(Bowman & Moran, 2017)
Painting steel	Repairs localized areas where the steel coating is damaged to prevent corrosion of steel bridge elements.	(Bowman & Moran, 2017)
Removing channel debris	Prevents channel bed material from scoring.	(Bowman & Moran, 2017)
Protecting against scour	Countermeasures to protect the substructure elements from undermining and failure due to scour.	(Bowman & Moran, 2017)
Lubricating bearings	Lubricate the metal bridge bearings to keep them in serviceable condition.	(Bowman & Moran, 2017)

making a region more competitive. Direct business activity outputs are considered as direct economic impacts. For example, a new highway project may lower consumers' costs to reach a department store.

2.2.1.2 Indirect Economic Impacts. Indirect impacts from a transportation investment refer to the benefits to suppliers from changes in business output. For instance, a new highway that reduced consumers' transportation costs allow consumers to access additional goods and services at a store. The store takes advantage of lower transportation costs by increasing production through hiring more workers and purchasing more supplies.

2.2.1.3 Induced Economic Impacts. Induced economic impacts happen when people in a region spend more money on buying higher quality goods and services than before because of their increased income. Following from the previous examples, the department store may respond to increased demand by hiring more workers and buying more inputs.

2.2.1.4 Dynamic Economic Impacts. Dynamic economic impacts represent changes in business locations, land value, and environmental conditions in the long run. For instance, in the case of the hypothetical department store, people and other businesses may move into the area in response to the new employment and market opportunities.

2.2.2 Tools for Measuring Economic Impacts

Economic multipliers or economic models (input output, econometric, and computable general equilibrium, CGE) are very important for converting the economic benefits into relevant economic impacts. Regional value added, employment, and income are commonly used performance measures of impact on economic development. Up to this point, efforts to develop tools for the economic analysis of transportation projects have been led by State DOTs, as well as individual firms. At the national level, a series of tools have been developed to assess the economic value of transportation projects at different stages in the planning process, with varying objectives and data requirements.

Figure 2.2 shows the existing tools for the assessment of social and economic effects of transportation projects, built upon the various methods offered in

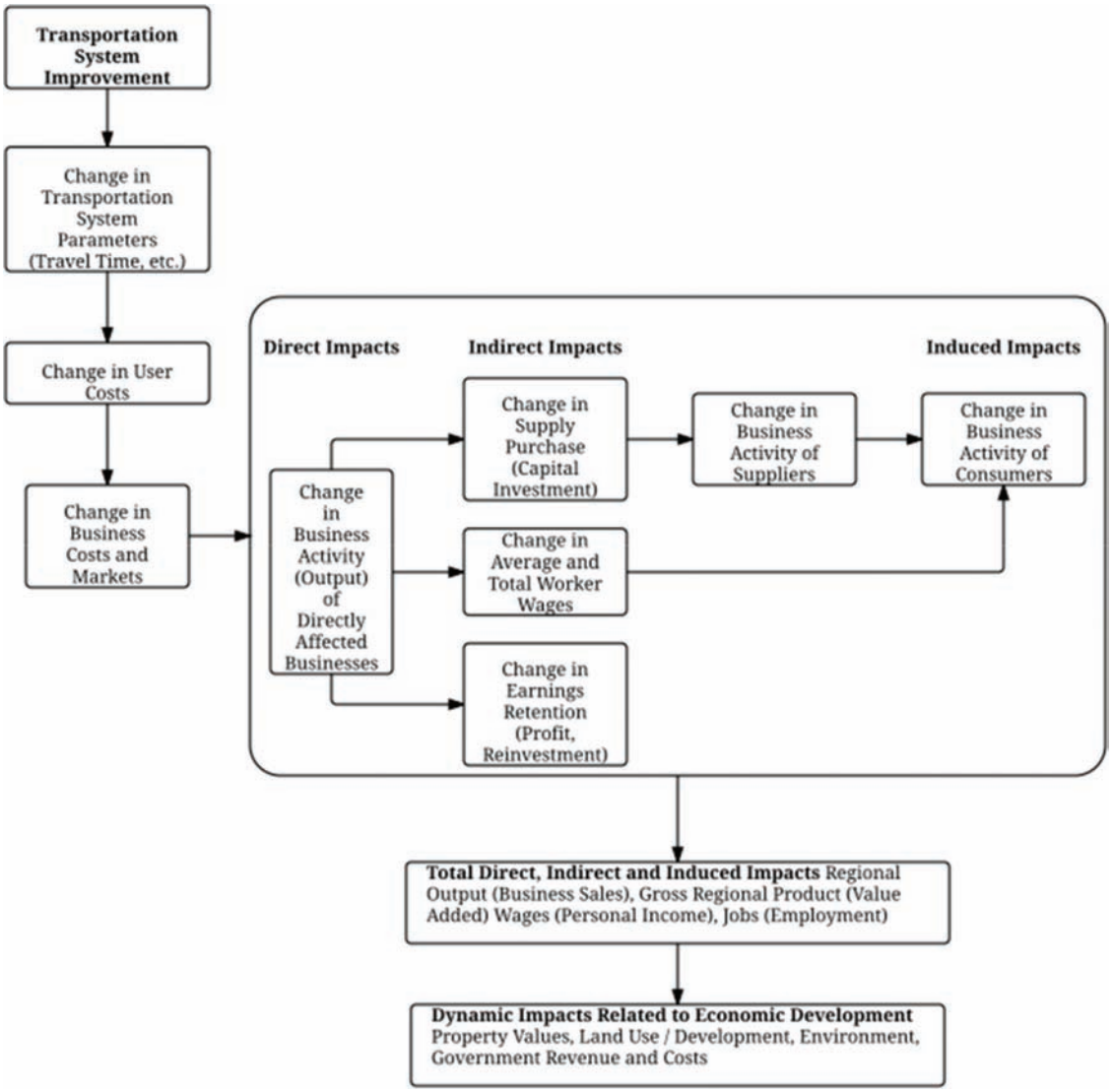

Figure 2.1 Categories of economic impacts. (Source: Weisbrod, 2000.)

NCHRP 456 (Forkenbrock & Weisbrod, 2001). The main contribution of the flowchart is to provide theoretical guidance to transportation professionals when they assess the economic impacts of non-traditional corridor improvements.

2.2.2.1 Static Input—Output Models. Static input-output models measure economic impact by inputting the direct impacts into the model and deriving the indirect and induced impacts as outputs. For one industry, the input-output models estimate how many units of input this industry requires from all industries to generate a unit of output within a certain range. Impact Analysis for Planning (IMPLAN) and Regional Input-Output Modeling System (RIMS-II) are widely used input–output models (Xiong, Fricker, & McNamara, 2012). The Long-Term Inter-Industry Forecasting Tool (LIFT) is another useful input-output model designed for the dynamic macroeconomic modeling of industry in the US (Inforum, 2019).

2.2.2.2 Dynamic Economic Models. Dynamic economic models are forecasting models that provide a more complex and comprehensive evaluation of a transportation investment's impact on economic development, including long-term impact estimation. Unlike static models, dynamic models calculate impacts and plug those results back into the model in a feedback loop that is run until an equilibrium is reached. Dynamic models may be input-output, CGE, or a combination of the two. TREDIS and REMI are two widely used tools with a variety of applications.

TREDIS. TREDIS is a web-based Transportation Economic Development Impact System that measures the economic output of transportation projects at the project development stage of the transportation planning process. Designed to help transportation planners conduct multiple economic-related analyses of transportation projects, TREDIS can evaluate the economic impacts and benefit-cost of a single transportation investment as well as assess the fiscal and public–private

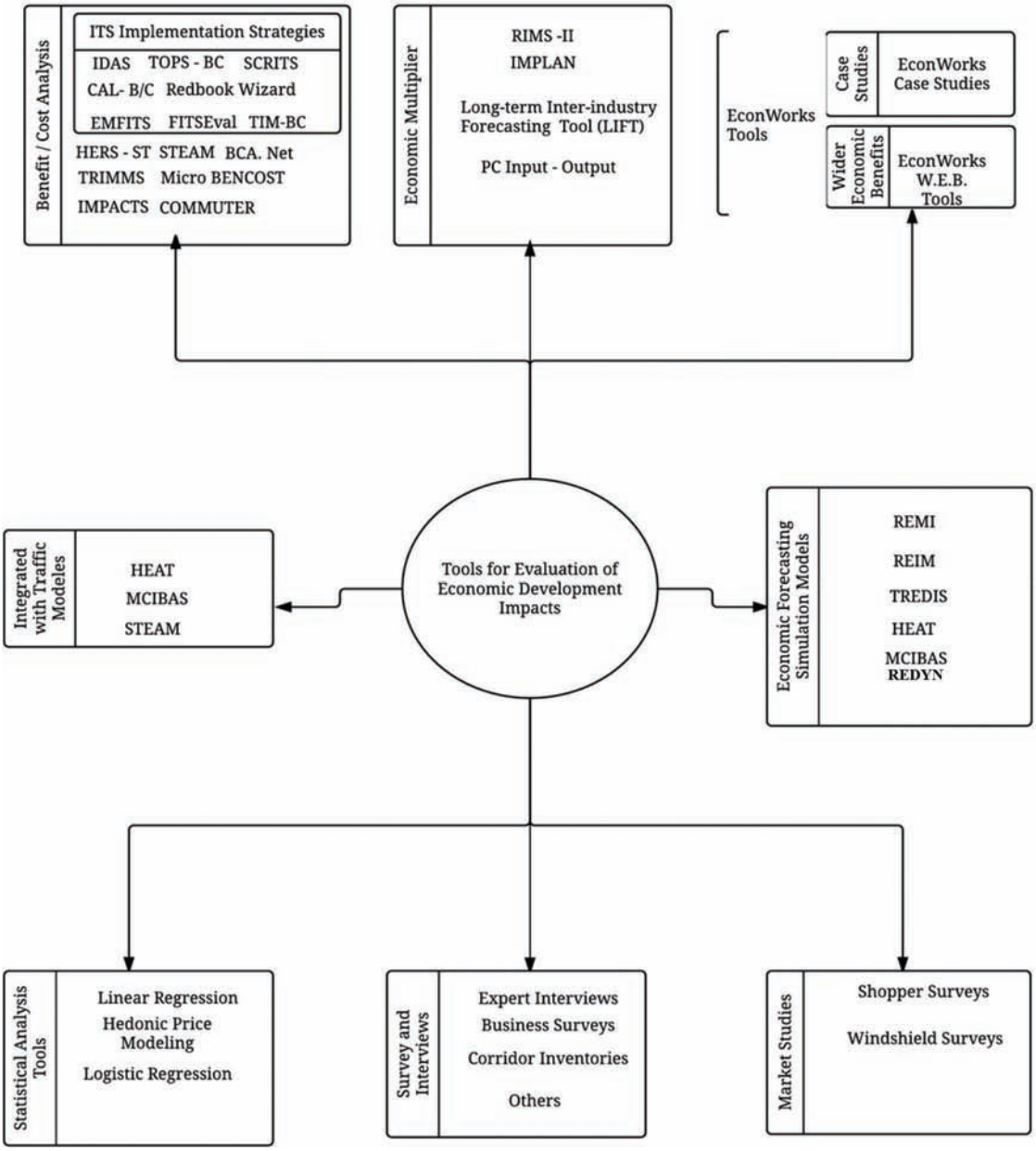

Figure 2.2 Existing tools for the evaluation of transportation projects.

financial impacts of a set of project alternatives (EDRG, 2014). TREDIS uses an IMPLAN-CRIO to perform the economic analyses. This is a modification of the static IMPLAN model which is intended to make it more dynamic.

REMI PI+. REMI Policy Insight is a dynamic forecasting model that investigates the effects of policy on regional economy and demography. REMI includes four major modeling approaches: input-output, computable general equilibrium models, econometric, and new economic geography, to capture inter-industry, long-term economic, demographic, and spatial dimension changes in the study region over the analysis period.

Five basic blocks make up the structure of REMI: (1) *Output:* The output block contains output, demand, consumption, investment, government spending, exports, imports, and changes in output caused by changes in the productivity of the intermediate inputs; (2) *Labor and capital demands*: The labor and capital demand block consists of labor intensity, productivity, and demand for labor and capital; (3) *Population and labor supply:* The population and labor block deals with the labor force participation rate and migration equations; (4) *Wages, prices, and profits:* The wages, prices, and profits block incorporates composite prices, determinants of production costs, the consumption price deflator, housing prices, and wage equations; and (5)

Market shares: The market share block is designed for estimating the interactions of local, interregional, and export markets in each region (REMI, 2015).

2.2.2.3 Transportation Economic Impact Analysis. In addition to models that estimate economic impacts due to a broad range of macroeconomic changes, there are also tools designed to estimate the impacts of specific transportation investments. These include MCIBAS and TOPS-EIA. There are three basic steps for estimating the economic impact of transportation investments. First, they estimate changes in performance measures, such as vehicle-miles traveled (VMT), vehicle-hours traveled (VHT), crashes, mode shift, trips, ridership, and/or vehicle occupancy that result from a project, program, or policy. Next, these changes are converted into transportation cost. Any reduction in cost is a benefit, and the results of this step can be used to perform benefit-cost analysis (BCA). Finally, the business share of these cost reductions are taken as inputs into a model to estimate the impacts to the wider economy.

MCIBAS & MCIBAS-SEAT. The Major Corridor Investment-Benefit Analysis System (MCIBAS) was developed by Cambridge Systematics and others for INDOT as a tool that could conduct the benefit-cost and economic impact analysis of added-capacity highway investments. MCIBAS is not a model, but a process that utilizes a variety of models and interfaces. At each step, the results from one model are converted to inputs for the next model. Changes in travel behaviour for build and no-build scenarios are estimated by the Indiana Statewide Travel Demand Model (ISTDM). A post-processor called NET_BC extracts crashes, VMT, and VHT for cars and trucks, and sorts them into speed bins. NET_BC output is entered into the Simplified Economic Analysis Tool (SEAT). This is an excel spreadsheet which monetizes the inputs, calculates the changes in transportation cost, and extracts the business share of them. It also performs a benefit-cost analysis. The business cost savings and accessibility improvements are entered into the Economic Impact Analysis System (IEAS), which is another spreadsheet. The EIAS takes these, estimates the changes in production costs, personal taxes, proprietor income, and business attraction by industry, and formats them for input into REMI's PI+ model. PI_ calculates the effects of these changes on the regional economy. The results are entered into the SEAT which summarizes them along with the benefit-cost results. The SEAT has a shortcut feature that uses multipliers to estimate the changes in employment, personal income, and gross regional product in lieu of PI+ results. In either case, MCIBAS is structured so that any changes are the result of improvements to the highway network, and not construction spending. More details on MCIBAS procedures may be found in Corradino (2012).

TOPS-EIA. The "Tool for Operations—Economic Impacts Assessment" (TOPS-EIA) tool calculates the economic impacts of corridor improvements. The tool builds upon a tool called, "Tool for Operations—Benefit Cost" (TOPS-BC), developed to perform benefit cost analysis of TSM&O strategies, and extends its capabilities and improves its user interface.

TOPS-EIA takes the expected impacts of each strategy on the corridor performance and translates them into, first, business cost savings and, second, economic impacts. To do so, the tool calculates the economic savings in travel time, travel time reliability, vehicle operating costs, and safety by mode and trip purpose during the entire life of the project. Subsequently, the benefits corresponding to trucks and auto-businesses are summarized in a measure of annual business cost savings. Finally, these business cost savings are translated into economic impacts through a set of statewide economic multipliers. Additional information on TOPS-EIA may be found at (Chacon-Hurtado, Yang, Gkritza, & Fricker, 2018).

2.3 Estimation of User Costs

Monetized user costs include vehicle operating, travel-time, and safety costs. These costs are usually related to physical conditions of the asset which translate into high user costs (Sinha & Labi, 2007). User costs need to be estimated in order to calculate business costs, which are then converted into economic impacts through the use of economic multipliers.

2.3.1 Vehicle Operating Cost

Vehicle operating cost (VOC) includes fixed costs, such as insurance and storage, and variable costs, such as energy use, maintenance, repairs, tire replacement, and mileage-dependent depreciation. To calculate the VOC savings of a transportation improvement, a new scenario should be compared with a base case scenario. Sinha & Labi (2007) present a framework to evaluate the VOC impacts of transportation improvements. First, it is necessary to identify the components of the vehicle operating cost. The factors that affect these components should also be identified. Some of the factors are vehicle/operator characteristics, economic factors, fixed asset characteristics, and policy factors. Other factors, such as road segment length and segment traffic volume affect VMT, which further adds to the VOC cost. The estimation of the VOC rates and VMT with and without intervention are then calculated, and the VOC user benefits are estimated. To assess the impacts, it is necessary to define the analysis area, describe the transportation intervention, and consider the base case scenario to establish a reference point. After that, it is necessary to identify the relevant values for the VOC factors. For that step, one needs to use the appropriate models or look-up tables to establish the VOC unit rates ($ per vehicle-mile). Additionally, the segment length of the project needs to be determined and multiplied by the estimated traffic volume to calculate VMT. VMT is multiplied by the VOC unit

rate to find the VOC for the scenario. This process is repeated for the build scenario.

2.3.2 Travel Time

Travel time savings typically constitute the largest fraction of economic benefits for most projects. The value of time in transportation represents the value of services, good, or some utility that can be produced in certain amount of time (Sinha & Labi, 2007). The less time spent traveling, the more time can be used in an alternative productive way. This has important implications, particularly in freight transportation, where extra time in transporting a product delays the opportunity of the consumer having it as well as prevents the carrier from taking on new business. In order to assess travel time costs, Sinha & Labi (2007) proposed a number of steps that should be followed. The first step aims to establish a base case scenario, where the year and the current conditions of the road or network are identified. After that, an estimation of the demand and capacity of the existing road is estimated to determine the travel speed. Once the speed is obtained, travel time is estimated. These steps are repeated for the alternative case scenario. Subsequently, the travel time saved due to the intervention is calculated and multiplied by the value of time. This is the travel time user benefit. The unit value of travel time is usually based on the hourly wage of the area. The default hourly wage rate used by this tool is the average wage of Indiana truck drivers according to BLS data. In some cases, it is necessary to repeat the previous steps in order to estimate travel time benefits for different vehicle classes, types of roads, or traveler classes.

2.3.3 Safety

The reduction of crash occurrence and severity is directly and indirectly linked with transportation projects. Although safety considerations were included primarily in projects related to roadway safety features, pavement preservation projects have also started to consider safety benefits, because poor pavement condition is associated with crash risk. To that end, Sinha & Labi (2007) developed a procedural framework for safety evaluation, which considers the change in crash frequency after a proposed transportation intervention and allows planners to quantify the associated monetary cost. This framework involves identification of the analysis area, description of the transportation intervention, and definition of the appropriate analysis approach. Different approaches can be considered to analyze the safety component of a transportation project. One approach is the use of statistical models that would estimate the crash frequency when accounting for road characteristics such shoulder type, pavement conditions, and other factors. After the appropriate approach is determined, the change in safety level and the overall safety costs are calculated. The unit monetary cost of crashes is usually a function of elements such as the market or economic cost and the non-market, or emotional, cost resulting from the crash. The following is an abridged annotated bibliography of additional studies consulted during the creation of the pavement preservation safety module.

2.3.3.1 Relationship between Road Surface Characteristics and Crashes on Victorian Rural Roads. This study suggests that the crash rate was higher for road sections with low macrotexture. The crash rates were also higher for roads with extreme roughness. However, no clear relationship emerged between rutting and crash rates (Cairney & Bennett, 2008).

2.3.3.2 Influence of Roadway Surface Discontinuities on Safety Sponsored by the Surface Properties. This study concluded that the most significant roadway disturbance is shoulder drop-off, closely followed by loose material on roadway. Fewer disturbances included potholes, rough roads, dips, and roadway design faults. In 21 of the 38 sites where drop-off was present, the authors determined that it appeared to be one of the causal factors leading up to a crash. The researchers also thought that edge drop was more likely to have been present when they investigated crashes on non-state-system roads than on state-system roads (Transportation Research Board, 2009).

2.3.3.3 Development of a Simplified Approach for Assessing the Level of Safety of a Highway Network Associated with Pavement Friction. This study reported that pavement surface friction affects highway safety and the probability of collision occurrence. The authors recommended a pro-active approach to address the friction-collision problem. Network-level friction testing should be carried out on an annual or bi-annual basis to screen for network and identify potential collision prone locations. Other factors, such as highway geometrics (curve radius, tangent length, super elevation, sight distance, etc.) influence driver, vehicle and highway safety. Unfortunately, at the time of the study, no comprehensive geometric data set was available. One of the most difficult aspects of the study was the integration and linkage of the data sets. A major reason for this issue is a problem many DOTs currently face—each data attribute was obtained from a different department within the agency (i.e., Pavement and Materials, Transportation and Safety, etc.). This demonstrates the benefits of integrating management systems such as a Traffic Safety Management System and a Pavement Management System (El Halim, Tighe, & Klement, 2009).

2.3.3.4 Incorporating Road Safety into Pavement Management: Maximizing Surface Friction for Road Safety Improvements. The results of the analysis did not indicate a relationship between crash frequency and pavement skid friction. Although some evidence suggests that the number of wet pavement crashes increased as the pavement life increased (and skid friction values

decreased), the frequency of crashes was not sufficient to statistically support this claim. Coefficients of determination and p-values were low for friction measurements taken at 40 and 50 miles per hour (mph). Nevertheless, the fact that the relationship seems to behave in an inversely proportional way (more crashes occurred at low friction numbers) is an important indication that skid resistance may indeed be a factor affecting wet weather crashes. Additional research has demonstrated that skid resistance is related to the incidence and frequency of crashes. An effective asphalt pavement asset management approach should include an annual testing program to monitor skid friction values. Friction Number (FN) values less than 35 should trigger a safety monitoring program for those pavements scheduled for future rehabilitation or reconstruction. The final aspect of the asset management program should include a detailed review of asphalt mix design and construction practices to assure that the initial FN value of newly constructed or rehabilitated pavement is maximized (Noyce, Bahia, Yambo, Chapman, & Bill, 2007).

2.3.3.5 NCHRP Guide for Pavement Friction. Empirical evidence from the research studies reviewed in this guide shows that vehicle crashes are more likely to occur on wet pavements (with lower friction levels) and that, as pavement friction levels decrease, there is a corresponding increase in crash rates. Research also shows that, when pavement friction falls below a site-specific threshold value, the risk of wet roadway crashes increases significantly (Kuttesch, 2004). The exact nature of the relationship between pavement friction and wet roadway crashes is site-specific, because it is defined not only by pavement friction but by many other factors. Thus, pavement friction and wet roadway crashes relationships must be developed for each of the sites that are typically present in a given pavement network (Hall et al., 2009).

3. PAVEMENT PRESERVATION EIA TOOL

3.1 Evaluation of Existing Tools

No single tool currently exists that can measure the economic impacts of pavement and bridge preservation projects at the sketch-planning level. However, based on research findings in SPR 3912 Part 2, one can calculate these impacts through the application of economic multipliers to changes in user costs, travel time costs, and safety costs (Chacon-Hurtado et al., 2018). Several pre-existing tools were identified during the literature review as being possible avenues in informing the research team of a means to calculate these costs. These included commercial software, such as MicroBENCOST and StratBENCOST, as well as publicly available software such as CAL-B/C, NCHRP 720, and HERS-ST. The following subsections provide a brief overview of each of the tools evaluated.

3.1.1 MicroBENCOST and StratBENCOST

Developed as part of an NCHRP project in the early 1990s, MicroBENCOST was designed to analyze various types of highway improvement projects at a corridor level. Benefit categories include user travel times, vehicle operating costs, and crashes. Cost categories considered by the tool include total initial cost of the highway improvement project, salvage value at the end of the analysis period, and rehabilitation and maintenance costs during the analysis period. Because MicroBENCOST aims to evaluate highway improvement projects at the corridor level rather than preservation projects at the sketch-planning level, it was not a good fit for SPR 3912's goals. Furthermore, this tool was developed over thirty years ago and its internal relationships may not align with modern conditions. As a DOS application, there were also concerns that it may not run well on modern computers without the use of a virtual machine environment.

StratBENCOST is an offshoot of MicroBENCOST. It was developed as part of NCHRP 2-18(4) in the late 1990s. It evaluates highway investments at the strategic level, and considers changes in user travel time, vehicle operating costs, safety costs, and emissions. Like Micro BENCOST, it weighs these benefits against costs such as capital costs, right-of-way costs, maintenance costs, and life cycle costs. Although a more recent program than MicroBENCOST, there was concern that Strat BENCOST outputs may also be outdated. Finally, because both MicroBENCOST and StratBENCOST are proprietary and closed-source in nature, it was difficult to determine what methods were used in calculations and how these methods could be applied to the needs of this study.

3.1.2 CAL-B/C

CAL-B/C is a Microsoft Excel spreadsheet-based software package produced by California Department of Transportation (CalTrans). It provides benefit-cost analyses of transportation capacity expansion projects at the sketch-planning level. Because it focuses on all transportation infrastructure capacity expansion rather than being limited to pavement and bridge preservation, CAL-B/C was considered an overly complicated tool for the purposes of this study. More information on CAL-B/C may be found at http://www.dot.ca.gov/hq/tpp/offices/eab/LCBC_Analysis_Model.html.

3.1.3 NCHRP 720

NCHRP 720 was a research effort that sought to estimate the effects of pavement condition on vehicle operating costs. In addition to releasing a report (Chatti & Zaabar, 2012), the project also developed a software package using Visual Basic for Applications (VBA) and Excel. The software allows users to calculate changes in user costs due to variations in pavement condition. Although the report provided a detailed description of the experimental methodology used in determining the

empirical relationships between pavement condition and vehicle operating costs, the underlying equations and coefficients of each cost component were not published. Similarly, as the VBA code for the tool was protected, it was impossible to view these relationships.

3.1.4 HERS-ST

HERS-ST is the state version of FHWA's HERS tool, which evaluates benefits and costs of a vast array of highway infrastructure interventions. Similar to other benefit cost tools, it considers vehicle operating costs, travel time costs, and safety costs, as well as changes in emissions, at corridor, network, and sketch-planning levels. More information on HERS-ST may be found at http://bca.transportationeconomics.org/models/hers-st. Although the tool itself is a compiled application (i.e., one cannot view the source code), the extensive documentation provided by FHWA allows users to view all equations used within the tool. Because of this, the research team ultimately chose to adapt HERS-ST's suite of equations to create the Pavement Preservation EIA tool.

3.2 Tool Development

Due to user familiarity with the interface of the TOPS-EIA tool developed for SPR-3912 Phase 2, the tools developed for Phase 3 are intentionally similar visually (Chacon-Hurtado et al., 2018). Microsoft Excel's VBA was again chosen as the development platform. As before, user inputs are coded as green cells, default/suggested values are in yellow cells, and intermediate and final outputs are in blue cells. The following subsections discuss the tool framework and development strategies for the Pavement Preservation Economic Impact Analysis (PP-EIA) tool and the Bridge Preservation Economic Impact Analysis (BP-EIA) tool, respectively.

3.2.1 Pavement Preservation Economic Impact Analysis (PP-EIA) Tool Framework

Figure 3.1 shows the framework used for the development of the pavement tool. The hexagons represent inputs, the rectangles are calculations, and the rhombuses are tool outputs. The tool is intended to operate as follows:

- Users can input the operating conditions, including annual average daily traffic (AADT), average vehicle speed, and length of roadway section, as well as pavement conditions (IRI) at two periods, T_0 and T_1. T_0 represents the IRI in a base case (e.g., the present or no-build scenario) condition, while T_1 represents the condition of the pavement at a later point in time (e.g., a future or build scenario). If the roadway segment has been treated, then the user may input a higher IRI value for the first condition and a lower IRI value for the second condition. Conversely, if the roadway segment has been allowed to deteriorate over time, then the user may input a lower IRI value for the first condition and a higher IRI value for the second condition.
- It is important to note that preservation treatments are not an explicit input; instead, the tool assumes that the change in pavement condition is due to a [lack of] preservation treatment.
- After the inputs have been entered, the tool will calculate the changes in travel time cost, vehicle operating costs, and safety costs. These outputs are shown in the brackets on the diagram, which indicates that these are considered intermediate outputs.
- The final module of the tool calculates the economic impacts. It allows users to either use the results from the preceding three modules as inputs or to directly enter alternative inputs. Through the use of MCIBAS-SEAT multipliers, the component costs are translated to changes in business savings, which are then translated into additional units measuring economic impacts—similar to the way in which SPR 3912 Phase 2's tool, TOPS-EIA, operated (Chacon-Hurtado et al., 2018).

The final results of the tool analysis (EIA Module) are a set of three metrics for economic impacts covering the entire time horizon as a consequence of the implementation of the work zone management system. The indicators of economic development are measured statewide and described as follows:

- *Gross Regional Product*, as a final demand, represents the sum of the consumption, investments, government

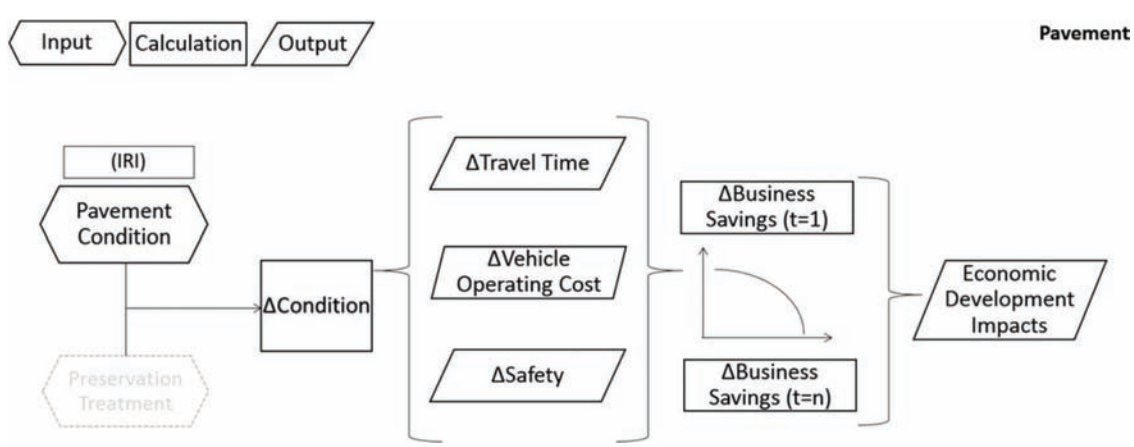

Figure 3.1 Framework of PP-EIA tool.

expenditure, and exports minus imports (REMI, 2015). It is expressed in millions of dollars for the year of analysis (see Input I).

- *Personal Income*, the income received by persons, including all sources. It represents the sum of wages, salaries, proprietor's income with inventory valuation and capital adjustments, rental income of persons with capital consumption adjustments, personal dividend income, personal interest income, and personal current transfer receipts, minus contributions for government social insurance. Personal income is expressed in millions of dollars in the year of analysis and represents the entire time horizon.
- *Employment* is represented by the estimated number of jobs, full-time plus part-time, by place of work. Part-time and full-time jobs are not counted equally (i.e., different weight). This indicator doesn't include family or unpaid workers. It is expressed in job-years. A job-year is the labor input equivalent of one person working full time for one year. This could be one person working full-time or a few people working part-time or overtime. This indicator will be calculated using the employment multiplier for the base year (2015).

As previously mentioned, the Pavement Preservation EIA tool uses an Excel interface with a VBA backend implementing simplified equations from the HERS-ST documentation. Because HERS-ST was developed to analyze specific roadways rather than assist in sketch level planning, several simplifying assumptions were made. These include, among others, the assumptions of no gradients, no horizontal or vertical curves, and a minimal number of intersections and driveways. The full list of simplifying assumptions is provided in Appendix A. In addition to relying on HERS-ST documentation, the pavement tool also used a few safety-related formulas found in the crash modification factor clearinghouse (CMF). In particular, crash rate calculations for rural roadways used the CMF formulas, because the HERS-ST formulas were insufficient, given the simplifying assumptions that were made. These simplifying assumptions were checked with safety experts at INDOT, who agreed that the assumptions were acceptable for sketch level planning. Equations used for calculations may be found in the Appendix A and B of this report.

Because the HERS-ST formulas were used as a starting point for most of the intermediate cost calculations, vehicle classification, which was originally coded to be consistent with FHWA's taxonomy, had to be transformed into categories compatible with HERS-ST. Table 3.1 shows the conversions for vehicle classes. These conversions are used in the calculations of vehicle operating costs and travel time costs in both the Pavement and Bridge Preservation EIA tools.

Finally, it is important to note that the HERS-ST equations use an abridged version of FHWA roadway functional classes. These are reflected in the pavement safety module. Unlike FHWA classifications, the HERS-ST roadway classes are rural two-lane, rural multilane, rural freeway, urban freeway, urban multilane, and urban two-lane roads.

TABLE 3.1
HERS and FHWA Vehicle Classification Schema

HERS Class	Description	FHWA Class
1	small car	1, 2
2	med/large car	2
3	4-tire vehicle	3
4	6-tire truck	4, 5
5	3+ axle SU truck	6, 7
6	3-4 axle CU Truck	8, 9
7	5+ axle CU truck	10, 11, 12, 13

3.2.2 PP-EIA Tool Discussion

As a sketch-planning tool, the pavement tool calculates changes in user costs, and therefore economic impacts, as a function of changes in pavement surface condition (measured in IRI). While INDOT pavement experts have remarked that IRI is a lagging indicator, the research team has noted that there is a lack of research connecting alternative indicators of pavement surface condition with user costs. Thus, the tool relies on IRI rather than rutting, for instance. Additional details regarding the pavement tool, such as equations used, may be found in Appendix A.

Although the underlying HERS-ST equations use present serviceability rating (PSR) instead of IRI, the project team opted to use IRI in the tools, because that is the measure currently used by INDOT. In the literature, there are several ways of converting between the three commonly used methods of measuring pavement surface roughness, present serviceability index (PSI), PSR, and IRI. Additionally, these conversions depend on the pavement materials involved. For instance, Al-Omari and Darter (1994) examine PSR and IRI for asphalt-concrete (AC), composite (COMP), and Portland cement concrete (PCC) pavement types in Brazil, South Africa, Texas, and Pennsylvania (Al-Omari & Darter, 1994). They empirically derive the following relationships in which IRI is measured in inches per mile:

AC pavements

$$\mathrm{PSR} = 5 \text{ x } e^{-0.0038 \times \mathrm{IRI}}; \qquad \text{(Equation 3.1)}$$

COMP pavements

$$\mathrm{PSR} = 5 \text{ x } e^{-.0046 \times \mathrm{IRI}}; \text{ and,} \qquad \text{(Equation 3.2)}$$

PCC pavement

$$\mathrm{PSR} = 5 \text{ x } e^{-0.0043 \times \mathrm{IRI}}. \qquad \text{(Equation 3.3)}$$

One main takeaway is that there is a non-linear relationship between IRI and PSR, regardless of the pavement type. Because this tool is intended to examine effects of pavement deterioration at a network level, the tool uses a generalized PSR-IRI conversion found in the HERS-ST documentation, which does not differentiate between pavement types.

Because the Pavement Preservation EIA tool is intended to be used for sketch-planning purposes, it is

assumed that the user will have an AADT value in mind appropriate to the road segment under consideration. AADT is then divided into "counts" of vehicles by class using relative proportions of vehicles. These proportions are derived from 2016 AADT data represented by each of the FHWA Scheme of Vehicle Classifications. It was developed based on data originally exported from INDOT's online Traffic Count Database System (TCDS) in support of INDOT's report to Federal Highway Administration (FHWA) as part of the annual submittal to the Highway Performance Monitoring System (HPMS). While that data does not currently carry with it the Functional Classification (FC) of the roadway, to determine the FC, the FC asset in INDOT's Roads and Highways Inventory System was spatially joined to the Traffic Count Station asset. The resulting table was brought into the workbook that holds the TCDS export and the VLOOKUP function used to associate the FC with each count station. Each station also had the percentage of AADT for each class calculated. These results were then analyzed using a pivot table with a filter to exclude any records that did not have a value for passenger vehicles, which is an indication that there was not vehicle class information available for that site. In this way, proportions of vehicle-by-vehicle class can be calculated for AADT across all roadway functional classes. Figure 3.2 illustrates this process.

3.2.3 Assumptions and Limitations

In both the VOC and safety modules, one key assumption is the lack of horizontal and vertical grades. Additionally, vehicle speeds are assumed constant and uniform across all vehicles. Finally, as previously mentioned, the tool asks users to input pavement condition in terms of IRI (in/mile) but the HERS-ST equations that were adapted used PSR. The HERS-ST documentation provides three equations for this conversion, one for each surface type (flexible, composite, and rigid). Rather than requiring an additional level of detail, the tool uses an average of these equations (i.e., average value of coefficients within conversion formulae).

In addition to sharing the three assumptions made in the VOC module, the safety module contains many more assumptions. First, it must be noted that the HERS-ST software uses a different scheme for categorizing functional class of roadways. The following table shows the correspondence between HERS-ST categories and FHWA roadway classification taxonomies (FHWA, 2013).

While most of the safety module is derived from HERS-ST, crash counts on rural two-lane roads are estimated using a different study (Labi, 2011). In this study, pavement condition is measured using the pavement condition index (PCI). The conversion from IRI to PCI relies on an empirically derived formula (Park, Thomas, & Wayne Lee, 2007); however, due to the nonlinear relationship, this conversion is only valid for IRI between the range of 46-127 in/mile.

Certain roadway characteristics are also assumed. For non-intersection rural two lane roads, the lane width is assumed to be 12 feet, shoulder width is 6 ft, roadside hazard rating is 3 (the default HERS-ST value), driveway density 8.4 per mile, crest curve grade rate is 0 (i.e., flat terrain), and the section length is

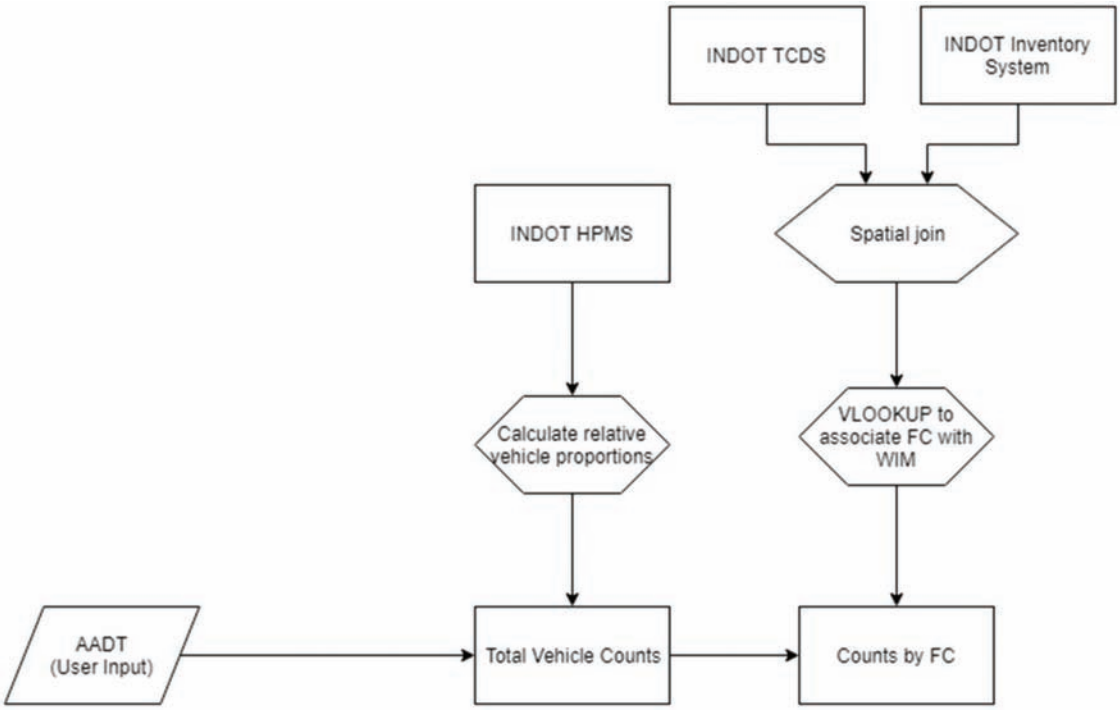

Figure 3.2 AADT to vehicle count framework.

assumed to be adjusted to exclude segments within 250 feet of an intersection. For rural multilane roads, the roadside hazard rating is set to 2.45, driveway density per mile is the unweighted average of sparse and dense rural multilane roads, and intersections per mile are assumed to be 0. The right shoulder width is assumed to be 12 feet and it is assumed that a barrier median exists and development along the roadside is rural. Urban multilane surface streets have 3 equations based on the type of the road section: 2-way with 1-turning lane; 1-way/2-way with median wider than 4ft, curbed, or positive barrier; and everything else). For estimating crash rates, the averages of the parameter coefficients were taken to formulate an aggregate equation.

It must be noted that crash outcomes are driven by speed of vehicles in this model, which are affected by IRI. As such, poor roadway conditions are associated with a reduction in speeds, which in turn decrease the likelihood of a fatality involved with the crash. It is expected that the calculated safety outcomes may be improved upon solely due to the speed reduction. Furthermore, because the economic cost per fatality is in magnitudes higher than the economic cost per injury, the tool will return seemingly counterintuitive results that imply IRI improvements lead to negative economic impacts solely due to the IRI-speed relationship.

3.3 Demonstration of the PP-EIA Tool

In the absence of data from a case study, the following example of the pavement tool in use applies realistic input values to estimate the economic impacts of changing pavement conditions. In this example, note that the second condition contains a higher IRI value than the first condition. This indicates that the roadway was allowed to deteriorate. After inputting the original speed of on the roadway and the first and second roadway conditions, as seen in Figure 3.3, the user can calculate vehicle operating costs.

Intermediate and final results are shown below (Figure 3.4). While the display defaults to show only aggregate effects on cars and trucks, users may also unhide rows to show VOC component costs by vehicle type. Positive final result cost values indicate that VOC has increased.

Upon completion of the VOC module, users can continue to the travel time (Figure 3.5) and safety (Figure 3.6) modules. The subsequent modules will automatically pull relevant user inputs from the VOC modules; thus, it is recommended that the analyst complete the VOC module first. The safety module includes a dropdown menu from which the analyst can select the roadway functional classification. As described previously, these roadway classes are unique to HERS-ST and do not directly follow FHWA classifications (see Table 3.2). It is important to note that the positive values in the final results of the travel time module reflect an increase in overall costs, while negative values in the results of the safety module indicate that safety costs have decreased. Additional details on user inputs and color-coding schema may be found in the accompanying user guide.

Once the VOC, travel time, and safety modules are completed, the analyst can begin to calculate the wider economic impacts in the final module (Figure 3.7). This module will automatically pull results from the previous modules; however, the analyst may enter alternate values. Default values are provided for trip purpose and modal split; again, the analyst may choose to use alternate values. The default value for total annual VMT is calculated by multiplying the AADT value from the safety module, the length of the roadway from the travel time module, and 365 (number of days in a year). Intermediate results (Figure 3.8) are presented in terms of business cost savings and translated into business impacts. MCIBAS-SEAT economic multipliers are applied to

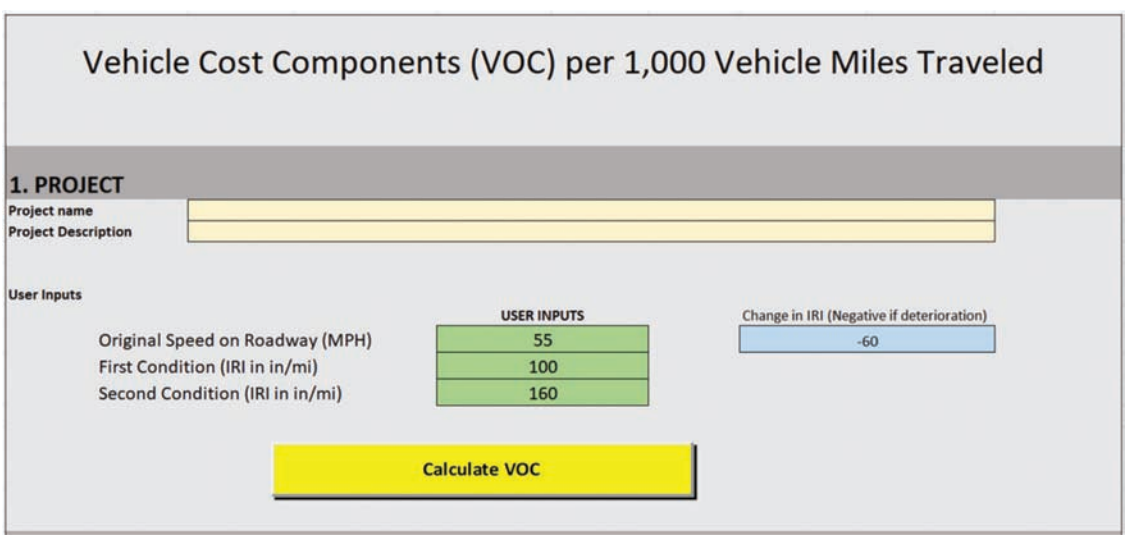

Figure 3.3 Pavement VOC example—user inputs.

2. INTERMEDIATE RESULTS

Vehicle Operating Costs by Vehicle Types and Operating Component ($/1,000VMT), First Condition

	Fuel	Oil	Tires	Maintenance and Repair	Vehicle Depreciation
All Car	$ 39.29	$ 1.28	$ 0.59	$ 80.52	$ 0.68
All Truck	$ 242.17	$ 2.85	$ 0.38	$ 78.95	$ 0.18

Vehicle Operating Costs by Vehicle Types and Operating Component ($/1,000VMT), Second Condition

	Fuel	Oil	Tires	Maintenance and Repair	Vehicle Depreciation
All Car	$ 47.42	$ 1.54	$ 0.74	$ 102.35	$ 0.70
All Truck	$ 250.33	$ 2.95	$ 0.42	$ 92.00	$ 0.19

3. FINAL RESULTS

Total Vehicle Operating Costs via Weighted Average of Traffic Counts ($/1,000 VMT)

VOC Component	Costs at First	Costs at Second	Difference in Costs
Fuel	$ 53.82	$ 57.13	$ 3.31
Oil	$ 0.98	$ 1.08	$ 0.10
Tires	$ 0.39	$ 0.46	$ 0.07
Maintenance/Repair	$ 31.32	$ 39.35	$ 8.03
Vehicle Depreciation	$ 0.25	$ 0.26	$ 0.01
Sum	$ 86.76	$ 98.28	$ 11.52

Figure 3.4 Pavement VOC module example—results.

Travel Time Costs

1. PROJECT

Project name

Project Description

	USER INPUTS		From VOC Sheet
First Freeflow Speed on Roadway (MPH)			55
Change in IRI		Negative if deterioration	-60
Length of Road (miles)	10		From BLS (IN truck driver avg)
Average Wage ($/hr)			$ 17.52

2. INTERMEDIATE RESULTS

Second Freeflow Speed (mph)	36.82
First Travel Time (min)	10.91
Second Travel Time (min)	16.30
Difference in Travel Time (min)	5.39
Cost of Travel Time Difference ($), per vehicle	1.57

3. FINAL RESULTS

Total Travel Time Costs ($/1,000 VMT) 157.28

Figure 3.5 Pavement travel time module example.

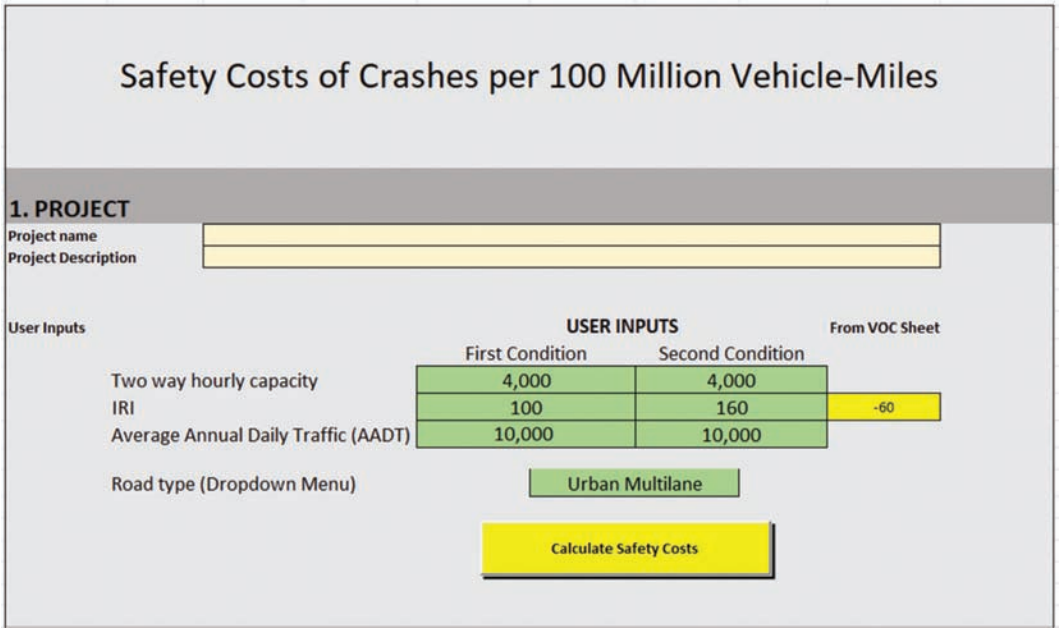

Figure 3.6 Pavement safety module example—user inputs.

TABLE 3.2
HERS and FHWA Roadway Classification Systems

HERS-ST Road Type	FHWA Roadway Classification
Rural two-lane	Rural minor arterial
Rural multilane	Rural other principal arterial
Rural freeway	Rural interstate
Urban two-lane	Urban other principal arterial
Urban multilane	Urban other freeway or expressway
Urban freeway	Urban interstate

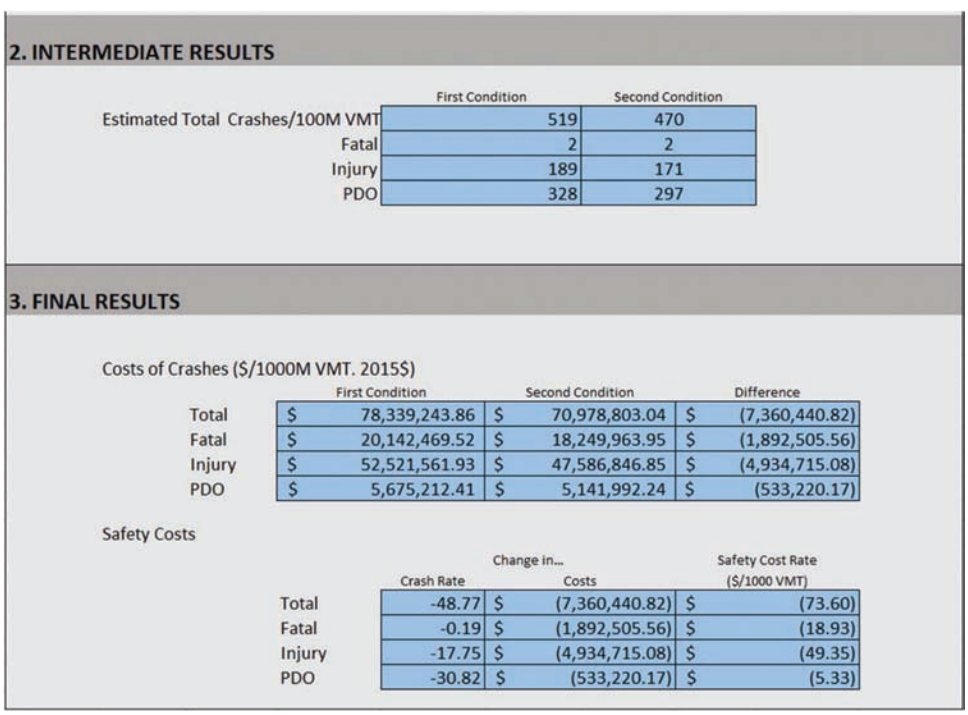

Figure 3.7 Pavement safety module example—results.

Economic Impacts Calculator

1. PROJECT INFORMATION

Project name	
Project Description	

	USER INPUTS	From Other Sheets
VOC Costs		$ 11.52
Travel Time Costs		$ 157.28
Safety Costs		$ (73.60)
Total VMT/Year		36500000

2. TRIP PURPOSE AND MODAL SPLIT

% Auto (All)		87.4%
% Truck		12.6%

Auto Trip Purpose	Percentages	
Commuting		23.99%
Personal		63.08%
Business		12.93%

3. RESULTS

BUSINESS COST SAVINGS ($/1000 VMT)

VOC IMPACTS	
Auto (Work)	$ (1.30)
Truck	$ (1.45)

TRAVEL TIME IMPACTS	
Auto (Work)	$ (17.77)
Truck	$ (19.82)

SAFETY IMPACTS	
Auto (Work)	$ 8.32
Truck	$ 9.27

BUSINESS IMPACTS ($/YEAR)	
AUTO (WORK)	$ (392,664.81)
TRUCK	$ (437,806.86)
TOTAL	$ (830,471.67)

ECONOMIC IMPACTS - Based on MCIBAS simplified economic analysis tool (SEAT)

ECONOMIC IMPACT MULTIPLIERS

Performance Measure	Annual Multiplier Per $10 Million in Business Cost Savings (in 2015 dollars)	
	Auto (Work)	Truck
Gross Regional Product (in million $)	$ 15.06	$ 17.74
Personal Income (in million $)	$ 18.42	$ 16.88
Employment (in job-years)	217.40	169.18

Performance Measure	Auto (Work)	Truck	Total
Gross Regional Product (in million $)	$ (0.59)	$ (0.78)	$ (1.37)
Personal Income (in million $)	$ (0.72)	$ (0.74)	$ (1.46)
Employment (in job-years)	-9	-7	-16

Figure 3.8 Pavement economic impacts analysis module example.

these business impacts to calculate economic impacts. Positive impacts are to be interpreted as benefits, while negative impacts are costs. Thus, for this example, allowing an urban multi-lane road with a 55 miles per hour speed limit to deteriorate from having an initial IRI of 100 in/mi to an IRI of 160 in/mi, wider economic impacts include single-year losses of $2.68M in gross regional product, $2.67M in personal income, and 28 job-years.

4. BRIDGE PRESERVATION (BP) EIA TOOL

4.1 Evaluation of Existing Tools

While there were existing pavement preservation benefit-cost analysis tools that could calculate user costs, the research team found scant evidence of similar tools for bridges, aside from PONTIS, which is a bridge management tool intended to help transportation agencies choose optimal preservation policies (FHWA, 2008). Similar to user costs associated with pavements, the user costs associated with bridges include travel time cost due to detours and vehicle operating cost.

Safety costs associated with bridges were not considered in the analysis because they primarily concern work zones, which may differ considerably based on the preservation treatment chosen for a bridge. The team looked to the research literature for relevant guidance and ideas to develop the bridge tool for this study. The following sub-sections summarize the results of the few studies that have presented ways to estimate user costs associated with bridge projects.

4.1.1 Bridge Life Cycle Cost Optimization

The objective of Safi's (2009) study was to become familiar with work zone and traffic characteristics, explain the possible related bridge user cost components, and provide a step-by-step procedure for computations that consider all traffic conditions related to bridge user costs (Safi, 2009). The analysis is focused on four components: traffic delay cost (TDC), vehicle operation cost (VOC), accident cost (AC), and failure

cost (FC). These four components sum up to give the total bridge user cost as shown below.

$$Bridge\ User\ Cost = TDC + VOC + AC + FC \quad \text{(Equation 4.1)}$$

To calculate the traffic delay cost (TDC), the difference between the time taken to cross the bridge and the time taken to travel along the detour or through the work zone are considered, as follows:

$$TDC = \sum_{t=0}^{T_k} TxADT_t xN_t x(r_t w_t + (1 - r_t)w_p)\frac{1}{(1+r)^t} \quad \text{(Equation 4.2)}$$

where

$$T = T_{wz} - T_0,\ T_o = \frac{L}{v_0} \quad \text{(Equation 4.3)}$$

T is the travel time delay for one vehicle in case of a work zone (hour);

ADT_t is the average daily traffic at time t, measured in number of vehicles per day;

N_t is the number of days needed to perform the work at time t (day);

r_t is the percentage of trucks from all ADT;

w_t is the hourly time value for one truck based on average hourly wage;

w_p is the hourly time value for one passenger car based on average hourly wage;

T_{wz} is the time taken to finish the detour or to cross the work zone (hour);

T_0 is the time taken to cross the bridge during the normal flow conditions (hour);

L is the affected length of road (km);

v_0 the traffic speed in the normal traffic flow conditions (hour);

v_{wz} is the work zone speed (km/hr); and

T_E is the bridge's expected lifespan.

To calculate the vehicle operation cost (VOC), fuel, engine oil, maintenance, and depreciation are considered. The expression to calculate this is:

$$VOC = \sum_{t=0}^{T_E} TxADT_t xN_t x(r_r O_r + (1 - r_t)O_p)\frac{1}{(1+r)^t} \quad \text{(Equation 4.4)}$$

The same parameters are used as before except for:

O_t is the average hourly operating cost for one truck, including its goods operation,

O_p is the average hourly operating cost for one passenger car.

To calculate the accident cost (AC), the following expression was used, in which AC represents the costs of increasing the risk of crashes, health-care costs, and deaths from the traffic disturbances due to work-zones on the bridge.

$$AC = \sum_{t=00}^{T_k} TxADT_t xN_t x(A_n - A_a)x[(C_F xP_F) + (C_l xP_l)]\frac{1}{(1+r)^t} \quad \text{(Equation 4.5)}$$

The same parameters used as before except for:

A_n The bridge accident rates during the normal condition (accident/vehicle/L/day),

A_a The bridge accident rates during work activities (accident/vehicle/L/day)

C_F The average cost per fatal accident to society

C_l The average cost per serious injury to society

P_F The average number of killed persons in bridge-related accidents, which is equal to 0.0009 (persons/accident) in Indiana.

P_F The average number of persons injured (not killed) in bridge-related accidents, which is equal to 0.991 (persons/accident) in Indiana in 2009 (more current values were not found).

Abed-Al-Rahim & Johnston (1995) proposed an alternative model for calculating the risk of accidents, which considers the ADT and the bridge length, as follows:

$$NOACC = [0.783x(ADT^{0.073})x(BL^{0.033})x(WZ+1)^{0.05}] - 1.33 \quad \text{(Equation 4.6)}$$

where,

NOACC the number of accidents per year;

BL is the bridge length in feet; and

WZ is the work zone width, in feet (equal to zero during normal conditions).

Finally, the failure cost (FC), was assessed using the following expression:

$$FC = \sum_{j=1}^{n} K_{H,j} R_j \frac{1}{(1+r)^j} \quad \text{(Equation 4.7)}$$

where R_j is the probability for a specified failure coupled to $K_{H,j}$. $K_{H,j}$ refers to the cots for the failure, accidents, rebuilding, user delay cost, and so on.

4.1.2 Bridge User Cost Estimation—A Synthesis of Existing Methods and Addressing the Issues of Multiple Counting, Work-Zones and Traffic Capacity Limitations

The study presents a synthesis of existing methods and addressing the issues of multiple counting, working zones, and traffic capacity limitation (Bai, Labi, Sinha, & Thompson, 2013). The authors argued that the poor condition of the bridge wearing surface can also cause additional VOC but that this is not addressed sufficiently in the literature. Work zone period has considerable user cost impacts, often due to reduced bridge width, lower speeds, or even a complete bridge closure. Bai et al. (2013) present a list of the expressions for calculating bridge detour costs due to the indicated deficiencies. The user cost due to the additional travel time costs (TTC) because of speed reduction is calculated by using the actual speed, the free flow speed, the volume over capacity (V/C) ratio, and parameters representing different highway classes and different speeds. The bridge user cost due to wearing surface roughness was also calculated using the additional VOC due to wearing surface described by the relationship between additional VOC and IRI as suggested in

(Barnes & Langworthy, 2003). A summary of the equations presented in this paper are found below. Note that Bai et al. (2013) did not examine safety costs.

Travel time cost is calculated using the following expression:

$$TTC_{CL} = \sum_{i=1}^{m} \left(\sum_{k=1}^{24} Addedtime\ (k) * ADT \right) * U_{TTC(i)} \quad \text{(Equation 4.8)}$$

where UTTC(i) is the unit TTC of vehicle class i; ADT(k) is the traffic volume in the kth hour;

Added Time (k), the added travel time during kth hour (hours/vehicle), is calculated as follows:

$$Addedtime(k) = Bridgelength * \frac{Speed_{free\,flow} - Speed_{Actual(k)}}{Speed_{free\,flow} * Speed_{Actual(k)}} \quad \text{(Equation 4.9)}$$

where $Speed_{Free\ flow}$ is ¼ free flow travel speed and $Speed_{Actual}(k)$ is ¼ actual travel speed in the kth hour. The actual travel speed can be derived from the Bureau of Public Roads function (Bai et al., 2013) as follows:

$$Speed_{Actual}(k) = \frac{Speed_{Free\,Flow}}{1 + a\left(\frac{V}{c}\right)^{b}} \quad \text{(Equation 4.10)}$$

where a, b are parameters representing different highway classes and different speed limits, and V/C is the volume/capacity ratio for the kth hour.

This paper also presents five equations for calculating VOC, as shown below:

Due to load capacity limit,

$$VOC = \sum_{i=1}^{m} U_{voc}(i) x DL x N_L(i) \quad \text{(Equation 4.11)}$$

Due to vertical clearance limit,

$$VOC = \sum_{i=1}^{m} U_{voc}(i) x DL x N_V(i) \quad \text{(Equation 4.12)}$$

Due to horizontal clearance,

$$VOC = \sum_{i=1}^{m} U_{voc}(i) x DL x N_H(i) \quad \text{(Equation 4.13)}$$

Due to poor alignment,

$$VOC = \sum_{i=1}^{m} U_{voc}(i) x DL x N_P(i) \quad \text{(Equation 4.14)}$$

Due to traffic flow limitations due to work zone

$$VOC = \sum_{i=1}^{m} U_{voc}(i) x DL x N_W(i) \quad \text{(Equation 4.15)}$$

where DL = detour length (miles);

m = number of vehicle classes;

$U_{VOC}(i)$ = unit VOC of vehicle class i (dollars/mile);

$U_{TTC}(i)$ = unit TTC of vehicle class i (dollars/hour);

SP(i) = average speed of vehicle class i on detour (miles/hour); and

$N_L(i)$, $N_V(i)$, $N_H(i)$, $N_V(i)$, and $N_W(i)$ are the numbers of class i vehicles that detour due to load limit, vertical clearance limit, inadequate horizontal clearance limit, poor alignment, and work zone, respectively.

4.1.3 AASHTOWare (PONTIS) Bridge Management and Thompson, Sobanjo, & Kerr (2003)

Benefits of functional improvements in PONTIS are assessed in terms of user cost savings. The total user benefit of a project is equal to the weight given to user cost, savings in accident cost, VOC, and TTC. The accident user cost saving is calculated using the forecasted ADT on the bridge, estimate of the current accident risk per vehicle, estimate of the accident risk per vehicle after improvement, and average cost per accident. In terms of VOC, the number of cars detoured each day at the bridge, the average VOC per km of detour and the length of detour in kilometres are considered. TTC is a function of the number of vehicles detoured each day at the bridge, average travel time cost per hour of detour, detour distance for the bridge roadway, and speed on the detour route are considered in calculating the benefits.

User cost models are used in PONTIS to quantify the potential safety and mobility benefits of functional improvements to bridges. More than 70 relevant papers and reports were found, most of them from outside the field of bridge management. From the safety standpoint, the increased travel time resulting from the posting is regarded as a proxy for the safety-related user cost. This delay is calculated and used in the same way as VOC. Thompson et al. (2003) developed a new accident risk model for PONTIS in Florida. Finally, PONTIS considers three aspects of user costs: cost per accident, vehicle operating cost per kilometer, and travel time cost per hour. The cost per accident uses the A-B-C injury system, which can be updated to later years. In the case of the Florida study, VOC is taken from the Florida Trucking Association and US BTS (Thompson et al., 2003). Despite providing user costs at an intermediary step, PONTIS is designed to calculate these costs on an individual bridge-by-bridge basis, which makes it difficult to generalize to the sketch-planning level. Ultimately, it is for this reason that the development of the bridge preservation EIA tool was not based on the PONTIS software.

4.1.4 Effects of Bridge Surface and Pavement Maintenance Activities on Asset Rating

This paper investigates how standard asset maintenance treatments have affected asset surface ratings. Data are from INDOT's asset performance database and used to quantify the effectiveness of such treatments in order to identify the factors that influence such effectiveness. The study also makes use of cost and performance data to estimate the cost and effectiveness of these treatments. While the paper provided useful background material, the analysis of particular maintenance treatments ultimately proved to be too project-specific to be implemented in the Bridge Preservation EIA tool (Saeed et al., 2018).

4.1.5 Efficient Load Rating and Quantification of Life Cycle Damage of Indiana Bridges due to Overweight Loads

Keeping in mind that the tool that was being developed was intended for use in a network-level sketch-planning analysis, the research team looked to generalizable measures of bridge condition. One such condition that was considered, and ultimately applied, was the concept of load capacities on bridges due to structural deficiencies that needed maintenance or preservation work. Cha et al., (2016) examined the efficient load ratings of bridges in Indiana due to overweight loads using finite element analysis with realistic AADT values (Cha, Liu, Prakash, & Varma, 2016). In a follow-up study, the authors simulated the effects of increased natural damage that may occur due to either the bridge being located in a highly corrosive environment or insufficient maintenance, or both (Cha et al., 2016).

4.2 Bridge Preservation (BP) EIA Tool

4.2.1 BP-EIA Tool Framework

Figure 4.1 shows the framework used for the Bridge Preservation EIA (BP-EIA) tool. In many respects, it operates similar to the Pavement Preservation EIA tool. Users are presented with two initial modules, in which they can enter inputs such as AADT, average speed, and average hourly wage. Specific to the bridge tool, however, are options to choose the bridge load limit and detour length. This tool assumes that bridges being analyzed are structurally deficient, and some weight capacity limits are imposed as a result. This means that some vehicle classes may need to detour; however, it is up to the user to decide what the weight restriction is. A default value for detour length is provided, which is the average value of all Indiana bridge detours according to National Bridge Inventory (NBI) data.

Unlike the Pavement Preservation EIA tool, the Bridge Preservation EIA tool does not calculate safety costs associated with certain vehicle classes needing to detour. Thus, intermediate outputs are only changes in travel time costs due to detour and changes in vehicle operating costs due to detour. Like the pavement tool, these intermediate outputs are translated into economic impacts via MCIBAS-SEAT's CGE- and social accounting matrix-based Type II multipliers.

Unlike the PP-EIA tool, which could adapt pre-existing equations from HERS-ST and other available resources to fit the project requirements, there were no easily-accessible, pre-existing tools for sketch level bridge preservation impact assessments. Furthermore, calculation of safety outcomes would require significantly more data on detour routes than may be appropriate for sketch-planning analyses. Therefore, the BP-EIA tool does not contain a safety module. Rather, it calculates the economic impacts due to changes in travel time and vehicle operation costs. This implies that, if overall safety improves [or worsens] due to certain vehicle classes needing to detour, the tool may underestimate [or overestimate] economic impacts. The BP-EIA tool uses the same set of equations as the PP-EIA tool; these equations may be found in Appendix A.

4.2.2 BP-EIA Tool Discussion

The bridge tool calculates the travel time and vehicle operating costs due to bridge load limits, attributed to structural deficiencies of bridges in poor condition. While both INDOT and FHWA have equations for determining load limits, these equations require a considerable amount of knowledge of the bridge under consideration. Because this is a sketch-planning tool, the project team decided that a more general approach to determining bridge load limits needed to be undertaken. In order to determine the bridge load limits, the project team examined truck counts and weights

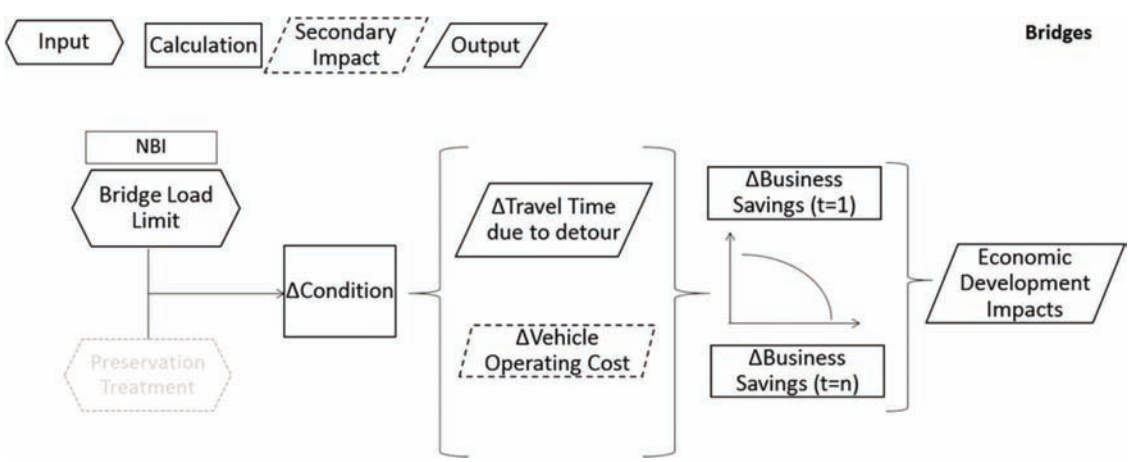

Figure 4.1 Framework of bridge tool.

observed by weigh in motion (WIM) stations over the course of a synthetic week for each truck class. The synthetic week includes all seven days—Sunday to Saturday—of the week; however, not all days were in the same week. Using this data, the histogram shown in Figure 4.2 was constructed to determine natural break-points in the weights. From the ensuing discussions, it was determined that the break points should be set

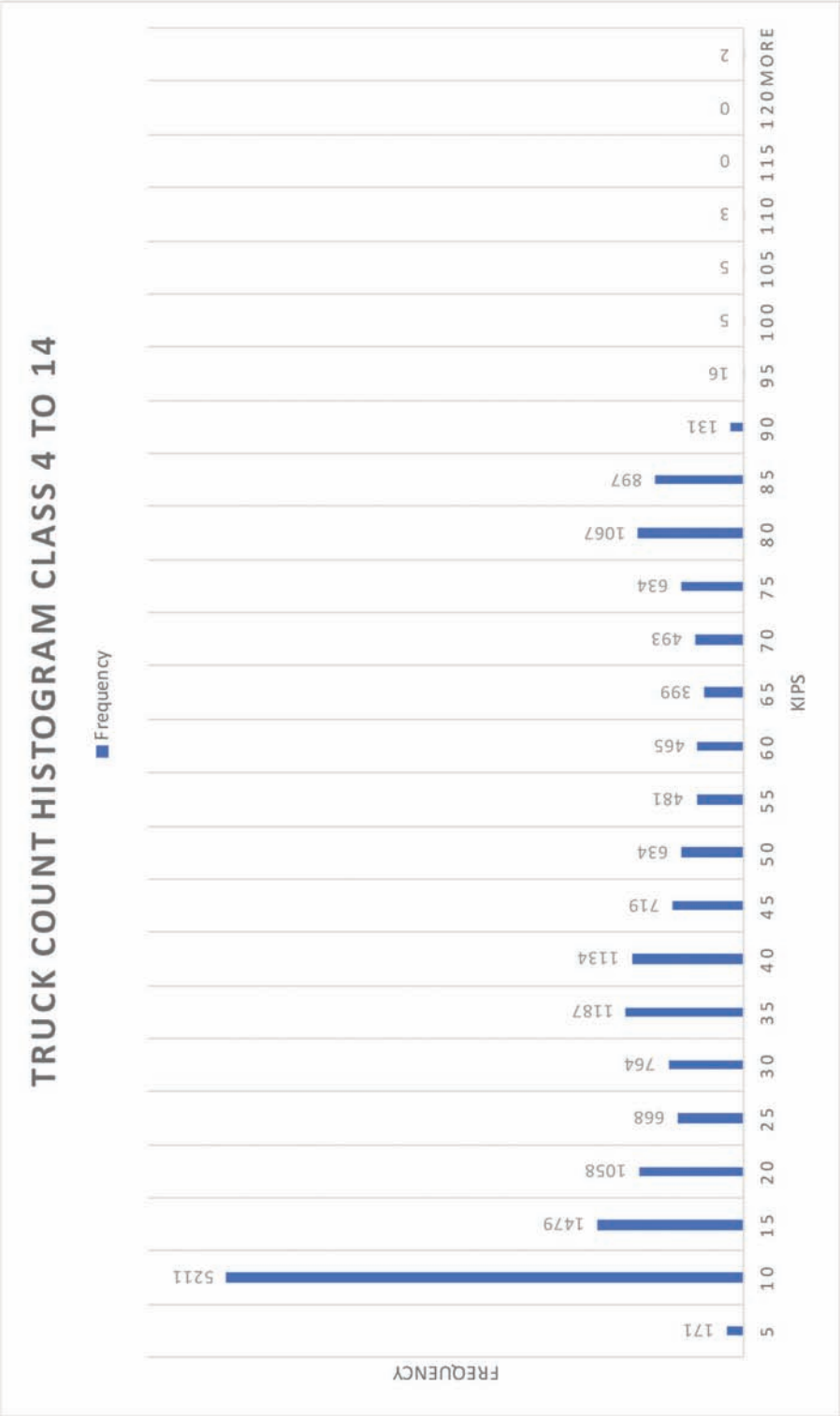

Figure 4.2 Truck weight distribution (all classes; in kips).

at 0, 25, 60, and 90 kips. Alternative methods of determining load limits were also considered, such as the use of k-means clustering, and a linear progression of weights by units of 10 kips. A bridge load limit of zero implies that the bridge is closed to all traffic, thus every vehicle regardless of class must detour. A bridge load limit of 25, 60, or 90 kips implies that the bridge is open to most traffic; however, trucks weighing more than 25, 60, or 90 kips, respectively, need to detour. Although the legal limit for most trucks is 80 kips, operators can apply for and obtain permits for overweight trucks. Thus, 90 kips is included as an additional upper bound to account for routes in which only overweight trucks are affected.

To determine the percentage of trucks that should detour given a weight limit, truck weight data was again needed. This truck weight data was extracted from INDOT's Traffic Count Database System (TCDS). After choosing an appropriate WIM station which was representative of all WIM stations across the state, 7 days (5 weekdays and Saturday and Sunday) worth of data was collected. This data was categorized by FHWA vehicle class with corresponding truck weight in Kips. A conversion table for kips and other units may be found in Appendix D. For classes 5 through 13, additional histograms and frequency tables were made showing the number of trucks (frequency) at the three pre-determined weight limits of 25, 60 and 90 kips. Based on this information, the percentage of trucks of each truck class could be calculated for purposes of deciding whether they would be affected by the user-specified bridge load limits. The changes in user costs associated with trucks that must detour can then be calculated based on the user's inputs for detour route length and detour route speed.

In addition to obtaining weights of all truck types to determine optimal load limits for the tool, it was also important to understand the distribution of weights for each truck class. Because less-than-truckload trucking practices may be common, using a linear distribution of truck weights by class could lead to gross under- or over-estimations of economic impacts of detours. The histograms in Appendix C show the weight distributions of each truck class. The multiple local maxima, especially in Class 5 and Class 9 trucks, indicate that less than truckload trucking practices have large impacts on weight distributions. As truck counts for each truck class were collected, the tool can determine the percentage of trucks in each class that would need to detour. Thus, the tool can account for heterogeneous vehicle operating costs between truck classes. The final module of the tool calculates the wider economic impacts. These outputs are in terms of gross regional product, personal income, and employment (refer to Section 3.2.1).

4.3 Demonstration of the BP-EIA Tool

Similar to the numerical example showcasing the Pavement Preservation EIA tool in Section 3.3, this section provides a walkthrough of the Bridge Preservation EIA tool using realistic inputs. Figure 4.3 shows the user input section of the VOC module. If the input for detour length is left blank, the average detour length value will be used. Alternate weight limits can be selected via a dropdown menu accessed by clicking on the cell. In this example, a bridge suffering from a structural deficiency has a weight limit of 60 tons. The detour route has a speed limit of 35 mph and is 5.5 miles long. Further, this route has an IRI of 160 in/mi. After clicking the calculate button, intermediate and final results of the VOC module will be displayed.

Changes in VOC are due to detouring trucks given an imposed weight limit. The intermediate results show the components of VOC by truck type, while the final results show a weighted average of vehicle operating costs given truck class distributions. In this example, the detour caused an overall increase of $7.46/1000 VMT. After completion of this module, the analyst can move on to the next module to estimate travel time costs (see Figure 4.4).

Figure 4.4 shows the travel time module. The travel time module automatically pulls shared values from the VOC module, namely detour route speed and default detour route length. Once again, the analyst can leave the corresponding green cells blank to use these shared values. The analyst is asked to input the original route speed and AADT, as well as provide information on average hourly wage (or use the default value). The analyst should again select the weight limit; it is important that this is consistent with the value as was used in the previous module; otherwise, it may become difficult to interpret economic impact results. Upon calculation of travel time costs, users are shown intermediate and final results. These results are due to trucks that have to detour given the specified weight limit. In this example, total travel time costs amount to an additional $728.31/1000 VMT compared to if there were no detour.

The last module of the tool calculates the economic impacts given the user costs, VOC and travel time costs (Figure 4.5). This module is functionally identical to the Economic Impacts Calculator found in the Pavement Preservation EIA tool and discussed in Section 3.3. In this example, having trucks weighing over 60 tons detour to a route of 5.5 miles long, with a 35-mph speed limit, and an IRI of 160 led to single-year losses in gross regional product, personal income, and employment in job-years of $0.23M, $0.23M, and 2, respectively.

Vehicle Cost Components (VOC) per 1,000 Vehicle Miles Traveled

1. PROJECT

Project name

Project Description

User Inputs

Detour Route Speed (MPH)	35
Detour Length (mi)	
Detour IRI (in/mi)	160
Weight Limit (tons)	60

Average Detour Length
5.495

0 = All trucks detour

Calculate VOC

2. INTERMEDIATE RESULTS

Vehicle Operating Costs by Vehicle Types and Operating Component ($/1,000VMT), Detour Route

	Fuel	Oil	Tires	Maintenance and Repair	Vehicle Depreciation
6-Tire Truck	$ -	$ -	$ -	$ -	$ -
3+ Axle Single Unit Truck	$ 3.06	$ 0.07	$ 0.01	$ 1.24	$ 0.01
3-4 Axle Combo Unit Truck	$ 92.00	$ 1.70	$ 0.11	$ 14.45	$ 0.05
5+ Axle Combo Unit Truck	$ 140.22	$ 3.39	$ 0.10	$ 15.27	$ 0.05
All Truck	$ 58.06	$ 1.27	$ 0.05	$ 7.43	$ 0.03

3. FINAL RESULTS

Total Vehicle Operating Costs via Weighted Average of Traffic Counts ($/1,000 VMT)

VOC Component	Costs at Detour
Fuel	$ 6.35
Oil	$ 0.12
Tires	$ 0.01
Maintenance/Repai	$ 0.98
Vehicle	$ 0.00
Sum	$ 7.46

Figure 4.3 Bridge VOC module example.

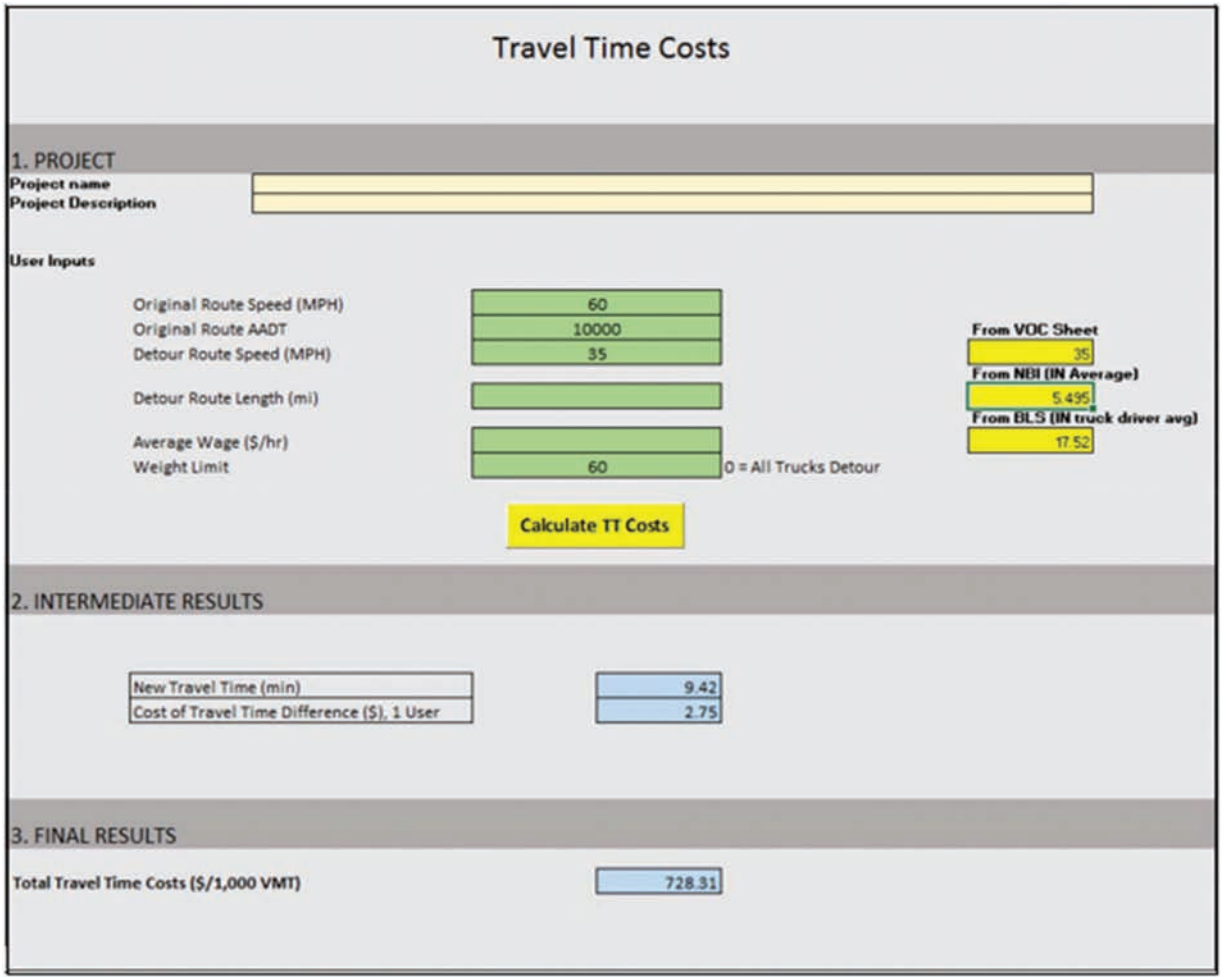

Figure 4.4 Bridge travel time module example.

Economic Impacts Calculator

1. PROJECT INFORMATION

Project name	
Project Description	

	USER INPUTS	From Other Sheets
VOC Costs		$ 7.46
Travel Time Costs		$ 728.31
Total VMT/Year		20,056,750.00

2. TRIP PURPOSE AND MODAL SPLIT

Modal Split	Percentages	Default Percentages
% Auto (All)		87.4%
% Truck		12.6%

Auto Trip Purpose	Percentages	Default Percentages
Commuting		23.99%
Personal		63.08%
Business		12.93%

3. RESULTS

BUSINESS COST SAVINGS ($/1000 VMT)

VOC IMPACTS	
Auto (Work)	$ (0.84)
Truck	$ (0.94)

TRAVEL TIME IMPACTS	
Auto (Work)	$ (0.84)
Truck	$ (0.94)

BUSINESS IMPACTS ($/YEAR)	
AUTO (WORK)	$ (33,840.00)
TRUCK	$ (37,730.36)
TOTAL	$ (71,570.35)

ECONOMIC IMPACTS - Based on MCIBAS simplified economic analysis tool (SEAT)

ECONOMIC IMPACT MULTIPLIERS

Performance Measure	Annual Multiplier Per $10 Million in Business Cost Savings (in 2015 dollars)	
	Auto (Work)	Truck
Gross Regional Product (in million $)	$ 15.06	$ 17.74
Personal Income (in million $)	$ 18.42	$ 16.88
Employment (in job-years)	217.40	169.18

Performance Measure	Auto (Work)	Truck	Total
Gross Regional Product (in million $)	$ (0.05)	$ (0.07)	$ (0.12)
Personal Income (in million $)	$ (0.06)	$ (0.06)	$ (0.13)
Employment (in job-years)	-1	-1	-1

Figure 4.5 Bridge economic impacts analysis module example.

5. CONCLUSIONS

The objective of this study was to develop tools that could calculate the economic impacts of pavement and bridge preservation projects at a sketch-planning level based on standard user benefits. The product of this study is a pair of quantitative user-friendly tools that can be used to analyze the economic impacts at a regional level of proposed pavement and bridge preservation and maintenance activities via a series of well-known indicators of economic impacts. The following steps were completed and presented in this report:

1. Several different options for practical research frameworks were explored in Chapter 2.
2. A tool was developed to assess the economic impacts of pavement preservation projects, partly based on HERS-ST (for equations that estimated user costs) following the methodology of the TOPS-EIA tool for converting user costs into economic impacts. The PP-EIA tool and its corresponding framework were described in Chapter 3.
3. A second tool was developed to assess the economic impacts of bridge preservation projects. The BP-EIA tool was discussed in Chapter 4.

The major contribution of this study is the demonstration of a feasible practical research framework that can be applied for economic impact analysis of pavement preservation and bridge preservation projects at the sketch-planning level.

5.1 Summary of PP-EIA and BP-EIA Tools

The PP-EIA and BP-EIA tools developed to calculate the economic impacts of pavement and bridge

preservation projects, respectively, allow users to estimate economic impacts at a sketch-planning level. To conduct a comparison of potential impacts from multiple preservation strategies, the analyst will need to use multiple instances of the tool (i.e., open another spreadsheet). By not being data hungry, the analyst can quickly gain insights on the statewide impacts of doing nothing and allowing pavement and bridges to deteriorate, or from the implementation of preservation that improve pavement and bridge conditions. These tools operate as follows. First, they calculate user costs, including VOC, travel time costs, and safety costs. User costs are converted into business cost savings which are subsequently converted into economic impacts. Economic impacts are reported in terms of gross regional product ($), personal income ($), and employment (job-years).

5.2 Applicability and Limitations of PP-EIA and BP-EIA Tools

The PP-EIA and BP-EIA tools are intended to provide the analyst with rough estimates of economic impacts at a statewide level and are most suitable for use in the sketch-planning phase of agency programming. In addition to the limitations outlined in the preceding tool discussion sections, the tools' assumptions and practicality brings a set of limitations that are opportunities for future improvements. These include:

- The economic multipliers reflect statewide impacts. Therefore, they are used independently of the region where the project is located.
- The tool emphasizes the assessment of the economic impacts caused by the savings of business travel costs from changes in pavement condition and bridge load limits. Future research could explore additional economic benefits triggered by improvements of market accessibility or enhancements of intermodal connectivity.

5.3 Implementation Plan

The PP-EIA and BP-EIA tools can be used for the screening of projects' impacts, project prioritization, or as part of multi-criteria analysis (MCA). Similarly, intermediate outputs of the tool such as user benefits (e.g., travel time savings) can be used in benefit-cost analysis (BCA). However, the latter will require the calculation of project costs, which these tools do not perform. For MCA, different indicators such as GRP, personal income, employment and any of the intermediate outputs generated by the tool can be incorporated directly as criteria in the decision-making process. The main advantage of MCA is its robustness with respect to double-counting or overlap of benefits. However, depending on the inputs used, the definition of "users" might need to be redefined, because the economic development benefits measured by the tool are statewide impacts. Furthermore, as part of this study, a set of training sessions, webinars, and presentations are provided for INDOT and metropolitan planning organizations (MPOs). These sessions cover both the theoretical background as well as a case study to demonstrate the use of the tools in action.

REFERENCES

Abed-Al-Rahim, I. J., & Johnston, D. W. (1995). Bridge element deterioration rates. *Transportation Research Record*, *1490*, 9–18. Retrieved from http://onlinepubs.trb.org/Onlinepubs/trr/1995/1490/1490-002.pdf

Al-Omari, B., & Darter, M. I. (1994). Relationships between international roughness index and present serviceability rating. *Transportation Research Record*, *1435*, 130–136. Retrieved from http://onlinepubs.trb.org/Onlinepubs/trr/1994/1435/1435-017.pdf

Bai, Q., Labi, S., Sinha, K. C., & Thompson, P. D. (2013). Bridge user cost estimation—A synthesis of existing methods and addressing the issues of multiple counting, workzones and traffic capacity limitation. *Structure and Infrastructure Engineering*, *9*(9), 849–859. https://doi.org/10.1080/15732479.2011.627348

Barnes, G., & Langworthy, P. (2003). *The per-mile costs of operating automobiles and trucks* (Report No. MN/RC 2003-19). Minneapolis, MN: University of Minnesota. Retrieved from http://hdl.handle.net/11299/909

Bowman, M. D., & Moran, L. M. (2017). *Bridge preservation treatments and best practices* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2015/22). West Lafayette, IN: Purdue University. https://doi.org/10.5703/1288284316007

Bureau of Design and Environment. (2010). Pavement preservation. In *Bureau of design and environment manual*. Retrieved from http://www.idot.illinois.gov/Assets/uploads/files/Doing-Business/Manuals-Split/Design-And-Environment/BDE-Manual/Chapter%2052%20Pavement%20Preservation.pdf

Cairney, P., & Bennett, P. (2008). *Relationship between road surface characteristics and crashes on Victorian rural roads*. Paper presented at ARRB Conference, 23rd, 2008, Adelaide, South Australia, Australia, July 30 to August 1, 2008. Retrieved from https://trid.trb.org/view/885955

Cha, H., Liu, B., Prakash, A., & Varma, A. H. (2016). *Efficient load rating and quantification of life-cycle damage of Indiana bridges due to overweight loads* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2016/06). West Lafayette, IN: Purdue University. https://doi.org/10.5703/1288284316329

Chacon-Hurtado, D., Yang, R., Gkritza, K., & Fricker, J. D. (2018). *Economic development impact of corridor improvements* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2018/01). West Lafayette, IN: Purdue University. https://doi.org/10.5703/1288284316644

Chatti, K., & Zaabar, I. (2012). *Estimating the effects of pavement condition on vehicle operating costs* (NCHRP Report 720). Washington, DC: Transportation Research Board. https://doi.org/10.17226/22808

Corradino. (2012). Updated MCIBAS procedures [MCIBAS training presented at the Division of Long Range Planning, Traffic Modeling and Counting, Indiana Department of Transportation]. Indianapolis, IN: Indiana Department of Transportation.

EDRG. (2014). *TREDIS user's manual version 4.0*. Boston, MA: TREDIS Software Group, Economic Development Research Group.

El Halim, A. A., Tighe, S., & Klement, T. (2009). Development of a simplified approach for assessing the level of safety of a highway network associated with pavement friction. In *Proceedings of the TRB 88th Annual Meeting*. Washington, DC: Transportation Research Board.

FHWA. (2008). *Pontis 4.3 bridge management system (Bridge management and inspection technologies)* (Report No. FHWA-RC-BA-L-04-0015). Washington, DC: Federal Highway Administration. Retrieved from https://www.fhwa.dot.gov/resourcecenter/teams/structures/str_5PON.pdf

FHWA. (2013). *Highway economic requirements system technical report*. Washington, DC: U.S. Department of Transportation.

FHWA. (2016). *Every day counts: An innovation partnership with states*. Washington, DC: U.S. Department of Transportation. Retrieved from https://www.fhwa.dot.gov/innovation/everydaycounts/reports/edc3_progressreport3.pdf

FHWA. (2018a). Dowel bar retrofit [Web page]. Retrieved from https://www.pavementinteractive.org/reference-desk/maintenance-and-rehabilitation/rehabilitation/dowel-bar-retrofit/

FHWA. (2018b). PCC patching [Web page]. Retrieved from https://www.pavementinteractive.org/reference-desk/materials/portland-cement/portland-cement-strength/pcc-patching/

Forkenbrock, D. J., & Weisbrod, G. E. (2001). *Guidebook for assessing the social and economic effects of transportation projects* (NCHRP Report 456). Washington, DC: National Cooperative Highway Research Program (NCHRP). Retrieved from http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_456-a.pdf

Hall, J. W., Smith, K. L., Titus-Glover, L., Wambold, J. C., Yager, T. J., & Rado, Z. (2009). *Guide for pavement friction*. Washington, DC: Transportation Research Board. https://doi.org/10.17226/23038

INDOT. (2017). Next level preservation [Web page]. Retrieved from https://www.in.gov/indot/3371.htm

Inforum. (2019). Lift model [Web page]. Retrieved from http://www.inforum.umd.edu/services/models/lift.html

Kuttesch, J. S. (2004). *Quantifying the relationship between skid resistance and wet weather accidents for Virginia data* (Master's thesis). Retrieved from VTechWorks (http://hdl.handle.net/10919/35551).

Labi, S. (2011). Efficacies of roadway safety improvements across functional subclasses of rural two-lane highways. *Journal of Safety Research*, *42*(4), 231–239. https://doi.org/10.1016/j.jsr.2011.01.008

Lee, J., & Shields, T. (2011). *Treatment guidelines for pavement preservation* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2010/01). West Lafayette, Indiana: Purdue University. https://doi.org/10.5703/1288284314270

McGee, H. W., Nabors, D., & Baughman, T. (2009). *Maintenance of drainage features for safety: A guide for local street and highway maintenance personnel* (Report No. FHWA-SA-09-024). Washington, DC: Federal Highway Administration. Retrieved from https://safety.fhwa.dot.gov/local_rural/training/fhwasa09024/fhwasa09024.pdf

NAPA. (2012). Thin overlays [Web page]. Retrieved September 5, 2018, from http://www.asphaltpavement.org/thinlay

Noyce, D. A., Bahia, H. U., Yambo, J., Chapman, J., & Bill, A. (2007). *Incorporating road safety into pavement management: Maximizing surface friction for road safety improvements* (Report No. MRUTC 04-04). Madison, WI: University of Wisconsin-Madison. Retrieved from http://www.wistrans.org/mrutc/files/04-04_MRUTC_FR.pdf

Ong, G. P., Nantung, T. E., & Sinha, K. C. (2011). *Indiana pavement preservation program* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2010/14). West Lafayette, Indiana: Purdue University. https://doi.org/10.5703/1288284314258

Park, K., Thomas, N. E., & Lee, K. W. (2007). Applicability of the international roughness index as a predictor of asphalt pavement condition. *Journal of Transportation Engineering*, *133*(12), 706–709. https://doi.org/10.1061/(ASCE)0733-947X(2007)133:12(706)

REMI. (2015). REMI homepage. Retrieved December 1, 2018, from https://www.remi.com/

Saeed, T. U., Qiao, Y., Chen, S., Alqadhi, S., Zhang, Z., Labi, S., & Sinha, K. C. (2018). *Effects of bridge surface and pavement maintenance activities on asset rating* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2017/19). West Lafayette, IN: Purdue University. https://doi.org/10.5703/1288284316573

Safi, M. A. E.-F. (2009). *Bridge life cycle cost optimization: Analysis, evaluation, & implementation* (Master's thesis). Royal Institute of Technology (KTH), Stockholm, Sweden.

Sinha, K. C., & Labi, S. (2007). *Transportation decision making: Principles of project evaluation and programming*. Hoboken, NJ: John Wiley.

Smith, K. D. (2009). *Load transfer restoration*. In *Transportation Research Board 88th Annual Meeting*. Washington, DC: Transportation Research Board.

Thompson, P. D., Sobanjo, J. O., & Kerr, R. (2003). Florida project-level models for Pontis. In *9th international bridge management conference* (Transportation Research Circular E-C049; pp. 70–84). Washington, DC: Transportation Research Board. Retrieved from http://onlinepubs.trb.org/onlinepubs/circulars/ec049.pdf

Transportation Research Board. (2009). *Influence of roadway surface discontinuities on safety: State of the art report* (Transportation Research Circular E-C134). Washington, DC: Transportation Research Board of the National Academies. Retrieved from http://onlinepubs.trb.org/onlinepubs/circulars/ec134.pdf

U.S. Department of Transportation. (2018). *Bridge preservation guide*. Washington, DC: U.S. Department of Transportation. Retrieved from https://www.fhwa.dot.gov/bridge/preservation/guide/guide.pdf

Weisbrod, B. A. (2000). *To profit or not to profit: The commercial transformation of the nonprofit sector* (first published 1998). Cambridge, England: Cambridge University Press.

WSDOT. (2018). Chip seal [Web page]. Retrieved from https://www.wsdot.wa.gov/Regions/Eastern/ChipSeal/

Xiong, Y., Fricker, J. D., & McNamara, K. T., & Longley, J. W. (2012). *Socioeconomic forecasting*. (Joint Transportation Research Program Report No. FHWA/IN/JTRP-2012/05). West Lafayette, IN: Purdue University. https://doi.org/10.5703/1288284314664

APPENDIX A: VOC MODULE EQUATIONS[1] AND SIMPLIFYING ASSUMPTIONS

Variable descriptions

Variable	Description
AES	Average Effective Speed, assumed constant
GR	Gradient, assumed zero
smcar	Small vehicles, corresponds to FHWA class 1 & 2
_fuel	Fuel consumption
_oil	Oil consumption
_tire	Tire wear and tear
_MR	Maintenance and repair
_dep	Depreciation
lgcar	Large vehicles, corresponds to FHWA class 2
trk4	4-tire trucks, corresponds to FHWA class 3
trk6	6-tire trucks, corresponds to FHWA class 4,5
trk3p	3+ axle single unit truck, corresponds to FHWA class 6,7
trk34CU	3-4 axle combo unit truck, corresponds to FHWA class 8,9
trk5pCU	5+ axle combo unit truck, corresponds to FHWA class 10,11,12,13

Small car VOC calculations

Note: Log in the equations below is the natural log (ln).
smcar_fuel: Fuel consumption for small vehicles, corresponds to FHWA vehicle class 1 and 2.
smcar_fuel: $(100.82-4.9713\times AES+0.11148\times AES^2-0.0011161\times AES^3+5.1089\times(10^{-6})\times AES^4+3.0947\times GR)$
smcar_oil: Oil consumption for small vehicles

When AES <55, smcar_oil = $\left(1.0435+\left(\frac{327.89}{1+(\mathrm{AES}+7.1977)}\right)\times\left(\frac{1+(\mathrm{GR}+8.0484)}{2.8984^2}\right)\right)$

When AES >= 70, smcar_oil = $\left(-170.4+34.02\times Log(AES)+\frac{1939}{\mathrm{AES}+0.27\mathrm{xGR}}\right)$

When AES AES >= 55 And AES < 70, smcar_oil=$(-170.4+34.02\times Log(AES)+\frac{1939}{\mathrm{AES}+0.4747\times\mathrm{GR}-0.003296\times\mathrm{AES}\times\mathrm{GR}})$

smcar_tire: small car tire wear and tear
smcar_tire=$(0.0604+2.92\times(10^{-8})\times AES^4+0.0000796\times AES^2+0.0274\times GR^2+0.074\times GR+0.0000568\times AES^2\times GR)$
smcar_MR: small car maintenance and repair
smcar_MR $=(48.3+(0.00865\times AES^2)+0.0516\times AES\times GR)$
smcar_dep: small car depreciation
smcar_dep $=(2.2+0.001586\times AES-0.38\times Log(AES))$

Medium and large car VOC calculations

lgcar_fuel: Fuel consumption for large vehicles
When AES <= 40, lgcar_fuel = $(88.556-3.384\times AES+1.7375\times GR+0.053161\times AES^2+0.18052\times GR^2+0.076353\times AES\times GR)$
Otherwise, lgcar_fuel = $(85.255-2.2399\times AES+2.7478\times GR+0.028615\times AES^2+0.41389\times GR^2+0.046242\times AES\times GR)$
lgcar_oil: Oil consumption for large vehicles
When AES >= 55 And AES < 70, $(lgcar_oil=9.5234-0.29873\times AES+0.0026913\times AES^2+0.28997\times GR^{1.00129})$
When AES >= 70, lgcar_oil=$\left(-173.3+34.6\times Log(AES)\frac{1973}{\mathrm{AES}+0.29\times\mathrm{GR}}\right)$

[1]All equations are derived from FHWA HERS-ST documentation (FHWA, 2013).

When AES < 55 And AES >= 15,
lgcar_oil = $(0.42295+0.35839\times AES-0.29984\times AES^2+0.0010392\times AES^3-0.000016196\times AES^4+9.3539\times(10^{-8})\times AES^5-0.0024\times GR)$
When AES < 15, lgcar_oil $=e^{(1.7713-0.12178\text{x}AES^{0.5})}\times Log(AES)+0.14636\times GR+0.11002\times GR^2+0.0082804\times GR^3)$
lgcar_tire: Tire wear and tear for large vehicles
When AES < 15, lgcar_tire $=(0.08+3\times(10^{-6})\times AES^3+0.029\times GR^2+0.0828\times GR+0.000056\times(AES^2)\times GR)$
When AES < 55 And AES >= 15, (lgcar_tire $=0.229+2.65\times(10^{-6})\times AES^3-0.0403\times Log(AES)+0.0214\times GR^2+0.00392\times AES\times GR)$
When AES >= 55, lgcar_tire = $(-0.2022+0.000237\times AES^2+0.0213\times GR^2-1.0322\times GR+0.3099\times Log(AES)\times GR)$
lgcar_MR: maintenance and repair costs for large vehicles
lgcar_MR = $(48.4+0.00867\times AES^2+0.0577\times AES\times GR)$
lgcar_Dep: Depreciation for large vehicles
lgcar_Dep = $(1.725+0.001892\times AES-0.311\times Log(AES))$

4-tire trucks VOC calculations

trk4_fuel: 4 axle truck fuel consumption
When AES <= 20, trk4_fuel = $(120.7-5.0201\times AES+0.1088\times AES^2+9.8816\times GR-1.3755\times GR^2+0.11582\times GR^3)$
When AES > 20 And AES < 55, trk4_fuel = $(115.41-3.6397\times AES+7.0832\times GR+0.050662\times AES^2-0.34401\times GR^2+0.096956\times AES\times GR)$
When AES >= 55, trk4_fuel = $\dfrac{(28.77+0.183655\times \text{AES}+3.34032\times \text{GR})}{1-0.0074966\times \text{AES}-0.049703\times \text{GR}}$
trk4_oil: 4 axle truck oil consumption
When AES < 50, trk4_oil = $(8.45+0.0000352\times AES^3-0.00567\times AES^2+0.37\times AES-4.12\times Log(AES))$
Otherwise, trk4_oil = $(16.41+0.004424\times AES2-0.5255\times AES)$
trk4_tire: Tire wear and tear for 4 axle truck
When AES < 15, trk4_tire = $(0.1294+3.64\times(10^{-6})\times AES^3+0.0324\times GR^2+0.1085\times GR+0.0000631\times AES^2\times GR)$
When AES >= 55, trk4_tire = $\text{Abs}-0.1554+0.000258\times AES^2+0.0205\times GR^2-0.05138\times GR+0.005058\times AES\times GR)$
When AES >= 15 And AES < 55, trk4_tire = WorksheetFunction.Max$(0.01,-0.2177+0.000208\times AES^2+0.02376\times GR^2+0.005895\times AES\times GR-0.03288\times Log(AES)\times GR)$
trk4_MR: maintenance and repair costs for 4 axle truck
trk4_MR= $(49.2+0.00881\times AES^2+0.0545\times AES\times GR)$
trk4_Dep: Depreciation for 4 axle truck
trk4_Dep = $(0.742+0.000589\times AES-0.1307\times Log(AES)\ )$

6-tire single unit trucks VOC calculations

trk6_fuel: 6 tire single unit truck fuel consumption
When AES < 55, trk6_fuel = $298.6-13.131\times AES+53.987\times GR+0.30096\times AES^2-4.7321\times GR^2-0.88407\times AES\times GR-0.0020906\times AES^3+0.22739\times GR^3+0.02875\times AES\times GR^2+0.0045428\times AES^2\times GR)$
When AES >= 55, trk6_fuel = $(101.5+0.000186\times AES^3+1.102\times GR^2+18.22\times GR)$
trk6_oil: 6 tire single unit truck oil consumption
When AES < 55, trk6_oil = $(13.98+0.0000603\times AES^3-0.00857\times AES^2+0.523\times AES-6.17\times Log(AES))$
Otherwise, trk6_oil = $(51.76+0.002513\times AES^2-14.29\times Log(AES))$
trk6_tire: 6 tire single unit truck fuel consumption tire wear and tear
When AES<15, trk6_tire = $(0.104+5.37\times(10^{-8})\times AES^4+0.0001578\times AES^2+0.1282\times GR^2+0.222\times GR+0.000168\times AES^2\times GR)$
Otherwise, trk6_tire = $e^{(-3.16-3.35\times 10^{-6})}\times(AES^3)-0.0308\times AES-0.00377\times AES\times GR)$
trk6_MR: 6 tire single unit truck fuel consumption maintenance and repair costs
trk6_MR = $(44.2+0.01147\times AES^2+0.1462\times AES\times GR)$
trk6_Dep: 6 tire single unit truck depreciation
When AES < 55, trk6_Dep = $(1.126+0.0028\times AES-0.247\times Log(AES))$
Otherwise, trk6_Dep $=0.2006+\dfrac{4.936}{AES}$

3+ axle single unit truck

trk3p_fuel: 3+ axle single unit truck fuel consumption
When AES <= 20, trk3p_fuel = $(254-3.0854\times AES-2.177\times GR-0.063346\times AES^2+24.848\times GR^2+4.3101\times AES\times GR+0.0012816\times AES^3-1.2432\times GR^3-1.6437\times AES\times GR^2+0.0013556\times AES^2\times GR)$
Otherwise, trk3p_fuel = $(1208.8-586.87\times Log(AES)+80.955\times(Log(AES))^2+93.99\times GR-13.477\times GR^2)$
trk3p_oil: 3+ axle single unit truck oil consumption
When AES < 55, trk3p_oil = $(20.2+0.0000724\times AES^3-0.0103\times AES^2+0.662\times AES-8.52\times Log(AES))$
Otherwise, trk3p_oil = $(22.85+0.006514\times AES^2-0.7188\times AES)$
trk3p_tire: 3+ axle single unit truck tire wear and tear
trk3p_tire = $(0.0896+0.0001308\times AES^2+0.0552\times GR^2+0.1181\times GR+0.00402\times AES\times GR)$
trk3p_MR: 3+ axle single unit truck maintenance and repair costs
trk3p_MR = $(46+0.008\times AES^2+0.146\times AES\times GR)$
trk3p_Dep: 3+ axle single unit truck depreciation
When AES < 55, trk3p_Dep = $(1.126+0.00279\times AES-0.247\times Log(AES))$
Otherwise, trk3p_Dep $=0.2006+\dfrac{4.936}{AES}$

3-4 axle combo unit truck VOC calculations

tr434CU_fuel: 3-4 axle combo unit truck fuel consumption
trk34CU_fuel = $(1087.9-576.71\times Log(AES)+82.039\times\dfrac{(\mathrm{Log(AES)})\hat{2}+22.325\times\mathrm{GR})}{(1-0.17121\mathrm{xLog(AES)}-0.035147\times\mathrm{GR})}$
trk34CU_oil: 3-4 axle combo unit truck oil consumption
trk34CU_oil = $(20.2+0.0000724\times AES^3-0.01034\times AES^2+0.662\times AES-8.52\times Log(AES))$
trk34_tire: 3-4 axle combo unit truck tire wear and tear
trk34CU_tire = $(0.15566-0.005847\times AES+0.041763\times GR+0.00021374\times AES^2+0.056992\times GR^2+0.0050156\times AES\times GR)$
trk34CU_dep: 3-4 axle combo unit truck depreciation
When AES < 55, trk34CU_Dep $=(0.354+0.000974\times AES-0.0806\times Log(AES))$
Otherwise, trk34CU_Dep $=0.05657+\dfrac{1.598}{AES}$

5+ axle combo unit truck VOC calculations

trk5pCU_fuel: 5+ axle combination unit truck fuel consumption
trk5pCU_fuel = $\dfrac{(1618.8-864.83\mathrm{xLog(AES)}+124.88\mathrm{x(Log(AES))}^2+32.087\mathrm{xGR})}{(1-0.16247\mathrm{xLog(AES)}-0.07074\mathrm{xGR}+0.011717\mathrm{x}GR^2-0.0011606\mathrm{xGR}^3)}$
trk5pCU_oil: 5+ axle combination unit truck oil consumption
When AES < 55, trk5pCU_oil = $(42.6+0.000189\times AES^3-0.0273\times AES^2+1.633\times AES-18.96\times Log(AES))$
Otherwise, trk5pCU_oil = $(9.383+0.003478\times AES^2-0.271\times AES)$
trk5pCU_tire: 5+ axle combination unit truck tire wear and tear
trk5pCU_tire = $(0.1432+1.248\times(10^{-6})\times AES^3+0.0639\times GR^2+0.1167\times GR+0.00332\times AES\times GR)$
trk5p_MR: 5+ axle combo unit truck maintenance and repair
trk5pCU_MR = $(44.9+0.01148\times AES^2+0.254\times AES\times GR)$
trk5pCU_Dep: 5+ axle combo unit truck depreciation
When AES < 55, trk5pCU_Dep = $(0.395+0.001215\times AES-0.0941\times Log(AES))$
Otherwise, trk5pCU_Dep = $0.05657+\dfrac{1.598}{AES}$

APPENDIX B: SAFETY MODULE EQUATIONS[2] AND SIMPLIFYING ASSUMPTIONS

Variable	Description	Default value	Notes
GR	Gradient	0	
lw	Lane width (feet)	12	
shw	Shoulder width (feet)	6	
rhr	Roadside hazard rating	3	
dd	Driveway density (#/mile)	8.4	
ccgr	Crest curve grade rate (%/100)	0	
adjsl	Section length adjusted to exclude segments within 250 feet of an intersection	NA	Assumed no intersections
cfac	Curve factor	Intermediate calculation	Assumed no curves
gfac	Grade factor	Intermediate calculation	Assumed no gradient
rhrrml	Roadside hazard rating for multilane roads	2.45	
ac	Access control; 1 = full or partial, 0 = none	0	
ddrml	Driveway density per mile for rural multilane roads; 0.41 for rural type, 5.6 for dense	3.005	Averaged the two
intspm	Intersections per mile; max=10	0	Assumed no intersections
rpa	Segment is a rural principal arterials and rural interstate(=1), 0 12otherwise	1	
shldw	Right shoulder width in feet	12	
medw	Median width in feet; 50 if positive barrier median	50	Max value is 50
devel	Type of development adjacent to rural multilane road, 1 for rural, 2 for dense	1	
TwoWayHourlyCapacity	Two way hourly capacity	4000	
a	Parameter used in urban multilane surface streets crash rate equation	97.833333333	
b	Parameter used in urban multilane surface streets crash rate equation	0.1665333333	
c	Parameter used in urban multilane surface streets crash rate equation	0.3013666667	
NSIGPM	Number of signals per mile for urban roads	1	Can't specify zero

Notes:

Log below represents natural log (ln):

Variables that end in "1" are for pre-build/initial scenario

Variables that end in "2" are for the 2nd scenario

Variables that end in "diff" are the difference between the two scenarios

Park et al. (2007) equation for PCI/IRI conversion: log PCI = 2 - 0.436 log (IRI); but limited to the range of 46-127 in/mile; may not be "good" for outside of this range

$PCI1 = e^{(2-0.436\times Log(IRI1))}$

$PCI1 = 100\times(IRI1^{-0.436})$

$PCI2 = e^{(2-0.436\times Log(IRI2))}$

$PCI2 = 100\times(IRI2^{-0.436})$

Road type: Rural two-lane

$$\text{Crash1} = 1.056\times\left(\frac{1}{1\times6\times6\times e^{\frac{(0.72-0.085\times \text{lw}-0.059\times \text{shw}+0.067\times \text{rhr}+0.0085\times \text{dd}+0.44\times \text{ccgr})}{1000}}}\right)\times \text{AADT1}\times\frac{\text{segmentLength}}{100000000}$$

When IRI1>10,

$PCI1a = e^{(2-0.436\times Log(10))}$

$PCIdiffa = PCI1 - PCI1a$

$CRASH1 = CRASH1\times(e^{(-0.1969\times PCIdiffa)})$

$$CRASH2 = (1.056\times\left(\frac{1}{1\times6\times6\times e^{\frac{(0.72-0.085\times \text{lw}-0.059\times \text{shw}+0.067\times \text{rhr}+0.0085\times \text{dd}+0.44\times \text{ccgr})}{1000}}}\right)\times \text{AADT2}\times\frac{\text{segmentLength}}{100000000}$$

$CRASH2 = CRASH2\times(e^{(-0.1969\times PCIdiff)})$

$fat_rural2 = CRASH2\times 0.01362$

[2]All equations are derived from FHWA HERS-ST documentation (FHWA, 2013).

$inj_rural2 = CRASH2 \times 0.561$
$pdo_rural2 = CRASH2 - fat_rural2 - inj_rural2$

Road type: Rural multilane

$CRASH1 = 132.2 \times (AADT^{10.073})$
$\times\ e^{(0.131\ \times\ rhrrml - 0.151\ \times\ ac\ +\ 0.034\ \times\ ddrml + 0.078\ \times\ intspm - 0.572 \times rpa + 0.0082 \times (12^{-lw}) - 0.094 \times shldw - 0.003 \times medw + 0.429 \times (devel - 1))}$
When IRI >11,
$PCI1a = e^{(2 - 0.436 \times Log(11))}$
$PCIdiffa = PCI1 - PCI1a$
$CRASH1 = CRASH1 \times (e^{(-0.1969 \times PCIdiffa)})$
Otherwise, $CRASH1 = CRASH1$
$fat_rural1 = CRASH1 \times 0.01685$
$inj_rural1 = CRASH1 \times 0.6317$
$pdo_rural1 = CRASH1 - fat_rural1 - inj_rural1$
$CRASH2 = 132.2 \times (AADT^{20.073}) \times e^{(0.131 \times rhrrml - 0.151 \times ac + 0.034 \times ddrml + 0.078 \times intspm - 0.572 \times rpa + 0.0082 \times (12^{-lw}) - 0.094}$
$\times\ shldw - 0.003 \times medw + 0.429 \times (devel - 1))$
$CRASH2 = CRASH2 \times (e^{(-0.1969 \times PCIdiff)})$
$fat_rural2 = CRASH2 \times 0.01685$
$inj_rural2 = CRASH2 \times 0.6317$
$pdo_rural2 = CRASH2 - fat_rural2 - inj_rural2$

Road type: Rural freeway

$CRASH1 = 17.64 \times (AADT1^{0.155}) \times e^{(0.0082 \times (12^{-lw}))}$
When IRI $>$ 13, $PCI1a = e^{(2 - 0.436 \times Log(13))}$
$PCIdiffa = PCI1 - PCI1a$
$CRASH1 = CRASH1 \times (e^{(-0.1969 \times PCIdiffa)})$
$CRASH1 = CRASH1 + (IRI1 - 12.789) \times 21.702264$
$fat_rural1 = CRASH1 \times 0.1408$
$inj_rural1 = CRASH1 \times 0.4546$
$pdo_rural1 = CRASH1 - fat_rural1 - inj_rural1$
$CRASH2 = 17.64 \times (AADT^{20.155}) \times e^{(0.0082 \times (12 - lw))}$
$CRASH2 = CRASH2 + (IRI2 - 12.789) \times 21.702264$
$CRASH2 = CRASH2 \times (e^{(-0.1969xPCIdiff)})$
$fat_rural2 = CRASH2 \times 0.1408$
$inj_rural2 = CRASH2 \times 0.4546$
$pdo_rural2 = CRASH2 - fat_rural2 - inj_rural2$

APPENDIX C: ADDITIONAL TRUCK WEIGHT HISTOGRAMS (VOLUMES FROM SYNTHETIC WEEK)

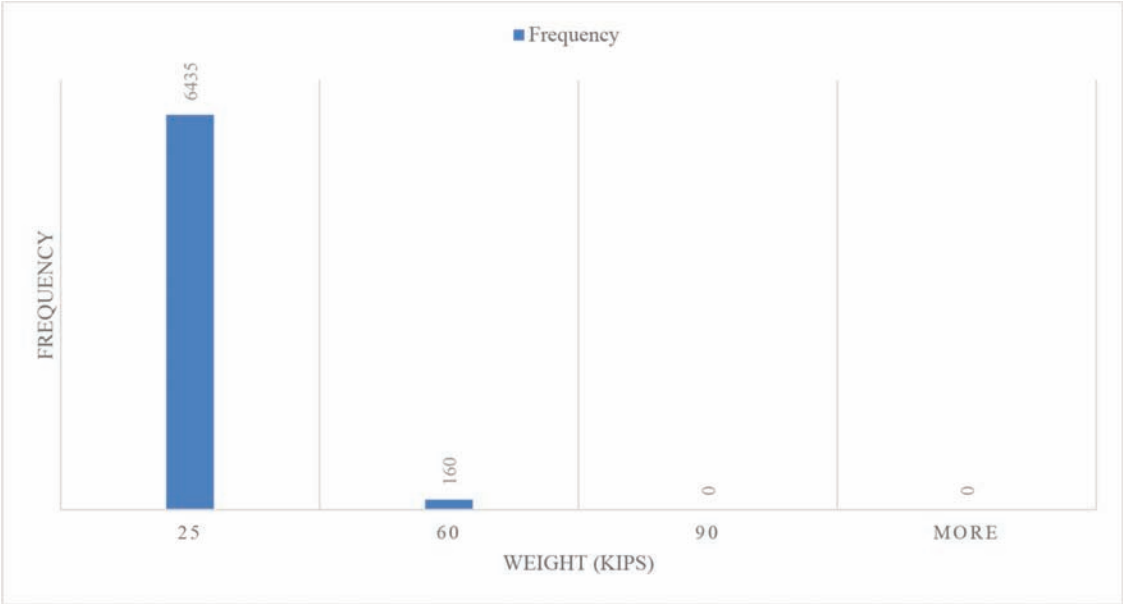

Figure C.1 Class 5 trucks.

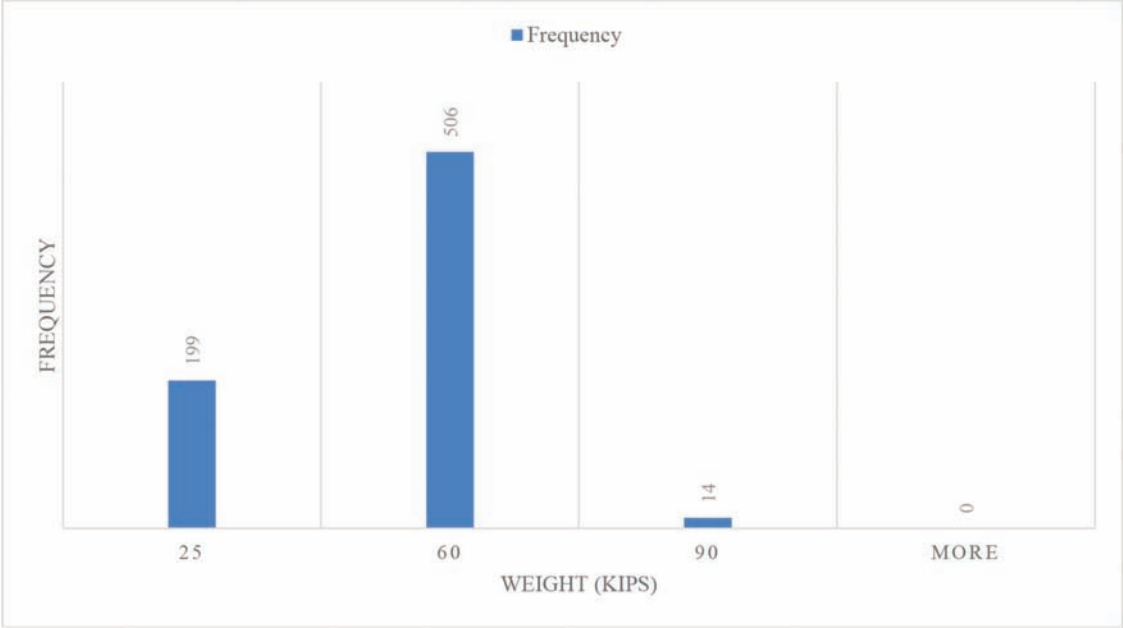

Figure C.2 Class 6 trucks.

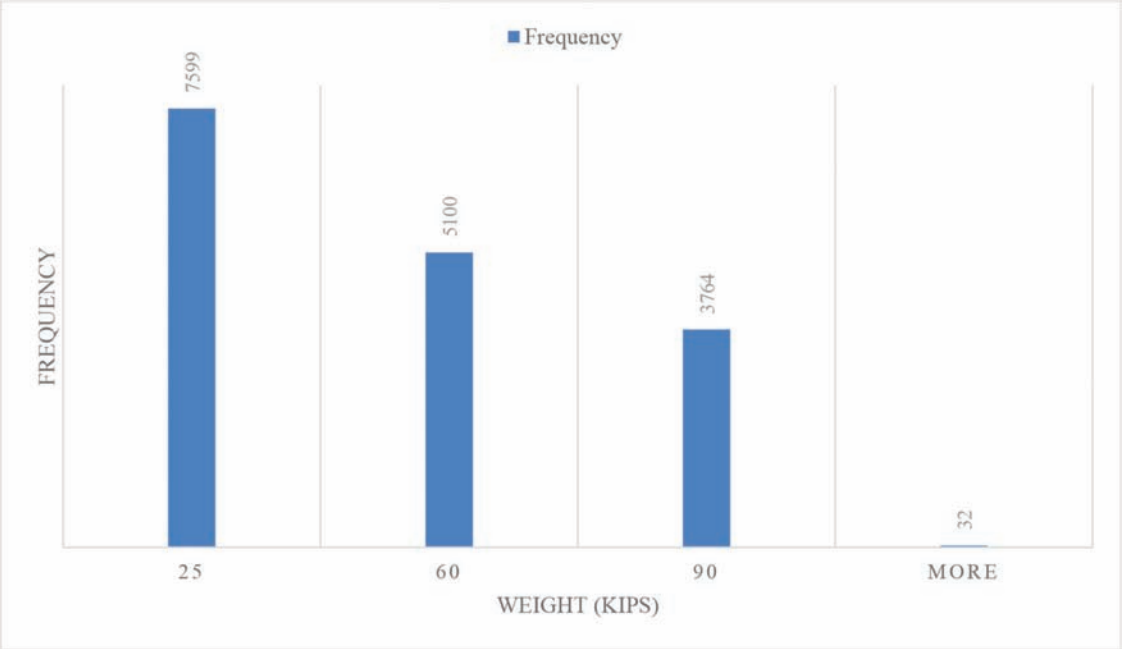

Figure C.3 Class 7 trucks.

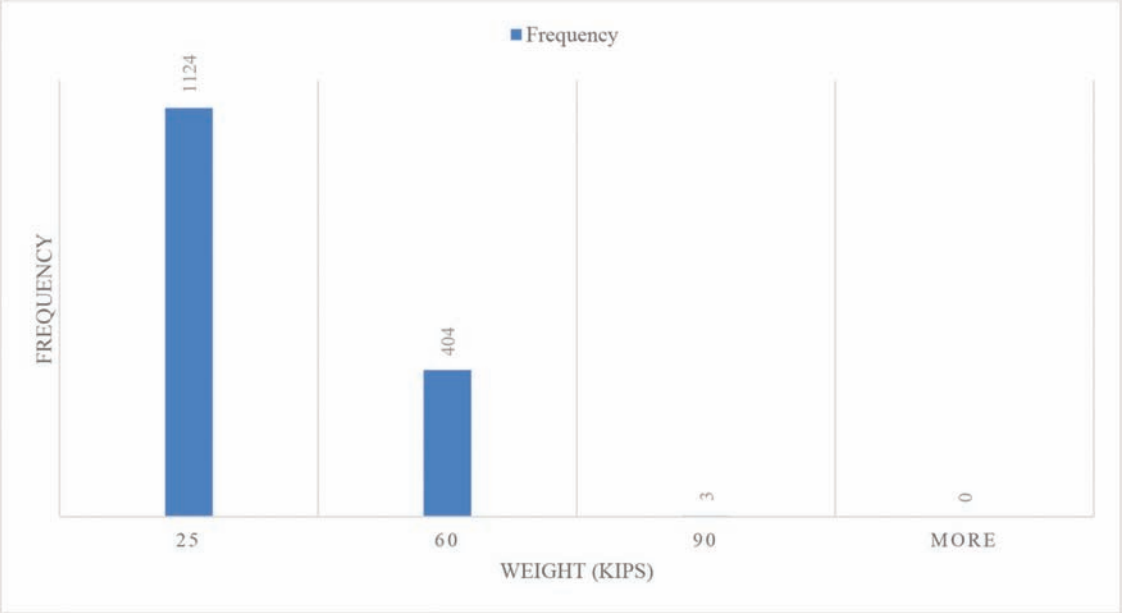

Figure C.4 Class 8 trucks.

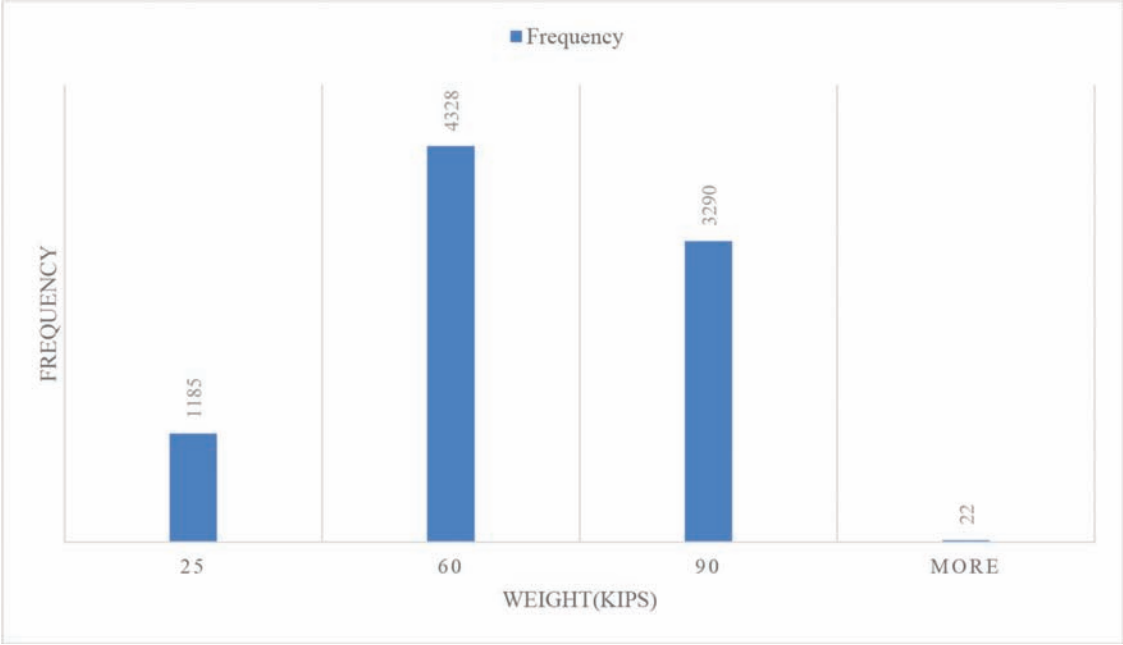

Figure C.5 Class 9 trucks.

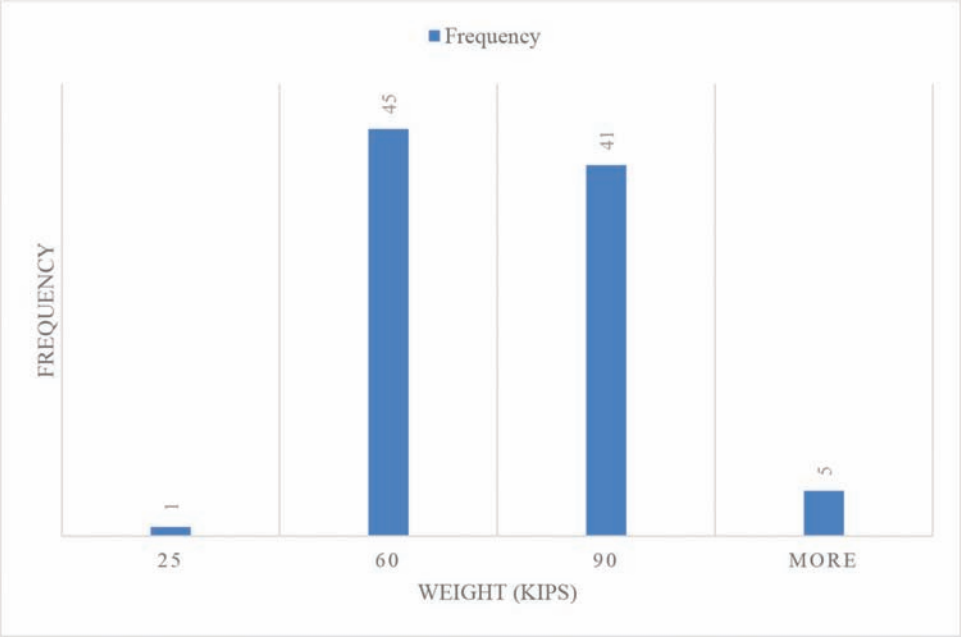

Figure C.6 Class 10 trucks.

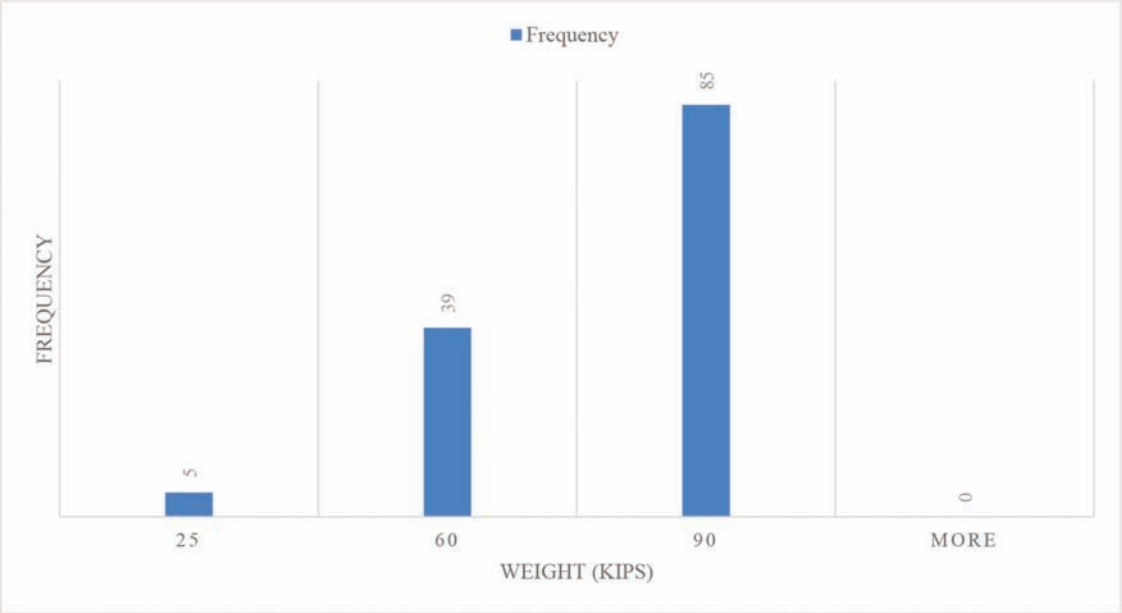

Figure C.7 Class 11 trucks.

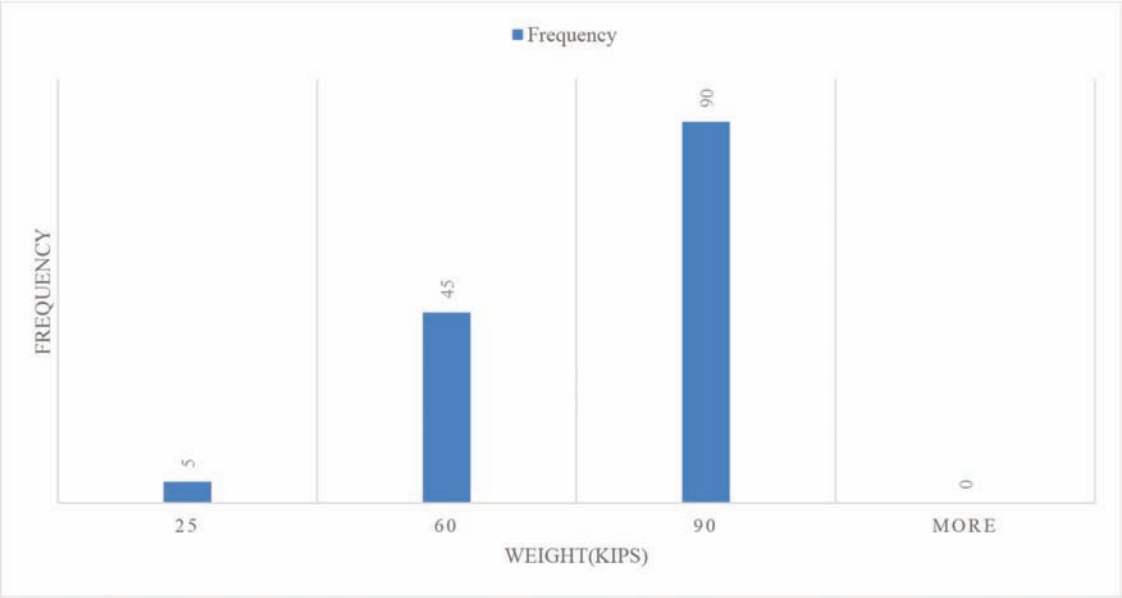

Figure C.8 Class 12 trucks.

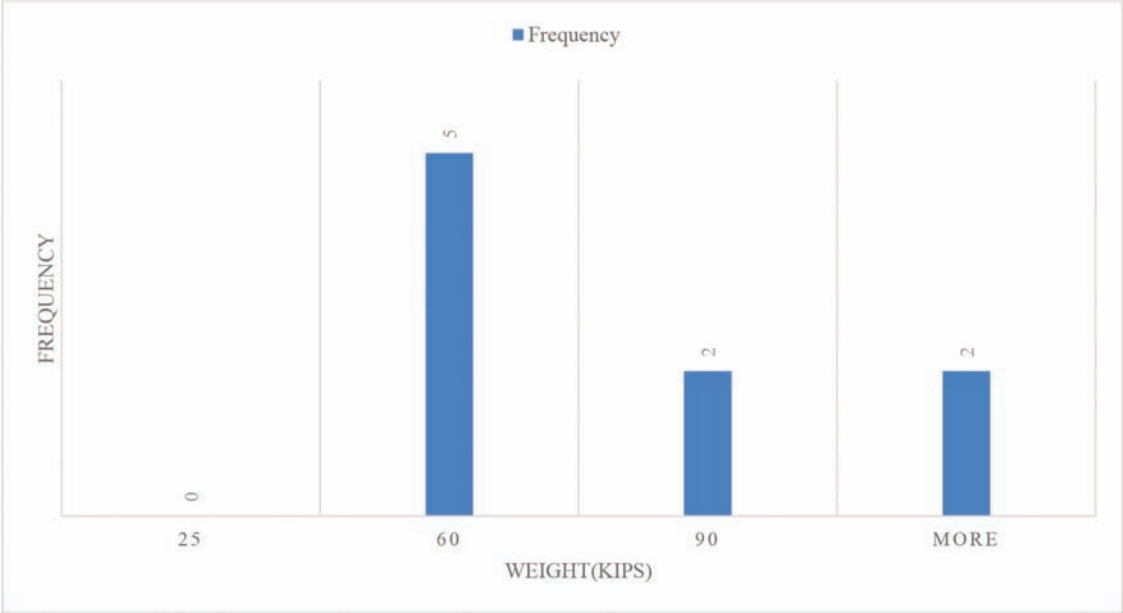

Figure C.9 Class 13 trucks.

APPENDIX D: UNIT CONVERSIONS

TABLE D.1
Table of Unit Conversions

Convert From	Convert To	Factor
Kips	Pounds (lb)	1000
Pounds (lb)	Kilogram (kg)	0.4536
Mile	Kilometer	1.61

About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,600 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at https://docs.lib.purdue.edu/jtrp/.

Further information about JTRP and its current research program is available at https://engineering.purdue.edu/JTRP.

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Recommended Citation

Ke, Y., Losada-Rojas, L. L., Chacon-Hurtado, D., Khair, S., Gkritza, K., & Fricker, J. D. (2019). *Economic development impact of preservation projects* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2019/05). West Lafayette, IN: Purdue University. https://doi.org/10.5703/1288284316882