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BRIDGE DECK SERVICE LIFE PREDICTION AND COST

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Supplementary Notes

Abstract

The service life of Virginia's concrete bridge decks is generally controlled by chloride-induced corrosion of the reinforcing steel as a result of the application of winter maintenance deicing salts. A chloride corrosion model accounting for the variable input parameters using Monte Carlo resampling was developed. The model was validated using condition surveys from 10 Virginia bridge decks built with bare steel.

The influence of changes in the construction specifications of w/c = 0.47 and 0.45 and w/cm = 0.45 and a cover depth increase from 2 to 2.75 inches was determined. Decks built under the specification of w/cm = 0.45 (using slag or fly ash) and a 2.75 inch cover depth have a maintenance free service life of greater than 100 years, regardless of the type of reinforcing steel. Galvanized, MMFX-2, and stainless steel, in order of increasing reliability of a service life of greater than 100 years, will provide a redundant corrosion protection system.

Life cycle cost analyses were conducted for polymer concrete and portland cement based overlays as maintenance activities. The most economical alternative is dependent on individual structure conditions.

The study developed a model and computer software that can be used to determine the time to first repair and rehabilitation of individual bridge decks taking into account the time for corrosion initiation, time from initiation to cracking, and time for corrosion damage to propagate to a state requiring repair.

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NOTICE

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Each contract report is peer reviewed and accepted for publication by Research Council staff with expertise in related technical areas. Final editing and proofreading of the report are performed by the contractor.

EXECUTIVE SUMMARY

Methodology

The purpose of the project was to develop service life estimates of concrete bridge decks and costs for maintaining concrete bridge decks for 100 years. With respect to service life estimates, a probability based chloride corrosion service life model was used to estimate the service life of bridge decks built under different concrete and cover depth specifications between 1969 and 1971 and 1987 and 1991. In addition, the influence of using alternative reinforcing steel as a secondary corrosion protection method was evaluated. Life cycle costs were estimated for maintaining bridge decks for 100 years considering the present age of the deck. Life cycle costs were estimated using both present worth and considering the inflated costs VDOT would expend to maintain concrete decks.

The scope of the service life estimates was limited to the validation of the probability based model using field survey data of 10 bridge decks built with bare steel and with a w/c = 0.47. Later age decks consisted of 16 decks built with a w/c = 0.45 and 11 decks built with a w/cm = 0.45. The 0.47 $^{w}/_{c}$ bridge decks were resurveyed 3 years after the initial damage survey to provide data on corrosion propagation rates. The supplemental cement materials were either slag or fly ash. Alternative reinforcing steels considered were galvanized steel, MMFX-2, and stainless steel. Cost to maintain concrete bridge decks for 100 years considered VDOT primary maintenance method, polymer overlays and rehabilitation method, concrete overlays either micro-silica or latex-modified concrete.

VDOT officials compiled a list of potential bridge decks and indicated whether or not fly ash or slag were used in the deck concrete, the type of reinforcement and the age of the structure. Additionally, the decks selected for surveying were evenly dispersed across the 6 climatic zones in Virginia. Core samples from the decks were used to confirm the composition of the concrete.

Bridge deck rehabilitation decisions are based upon the deterioration of the worst-span-lane of the deck. The right-hand lane normally receives more traffic and therefore deteriorates at a faster rate. For that reason, and due to safety and traffic control issues, only the right-hand lanes were surveyed. The deck survey included a visual survey, non-destructive testing, and the collection of 15 - 4 in concrete cores per deck.

Chloride titration data for diffusion constant (D_{ca}) and surface concentration (C_o), cover depth measurements, and the deck damage survey were used to estimate service lives. The estimate consists of three distinct time periods.

1. Time to corrosion initiation,
2. Time from initiation to cracking, and
3. Time for corrosion damage to propagate to a limit state.

The service life software used for this project, Bridge Corrosion Analysis (BCA), models the diffusion of chlorides using simple Fickian behavior with time-independent input parameters. The model simplifies the diffusion process to the extent that it can be easily used as a bridge engineering and management tool. A Fickian based diffusion model was used to allow for the easy incorporation of the stochastic nature of the input variables. BCA was developed as an Excel module, which was added to the standard Microsoft Office package.

The software used in this project uses a Monte Carlo statistical resampling technique to allow for the integration of input parameter variability into the model.
Monte Carlo Simulation (MCS) is defined as “any method, which solves a problem by generating suitable random numbers and observing that fraction of the numbers obeying some property or properties” (Weisstein, 2006). MCS takes into account the statistical nature of the input parameters by randomly selecting numerical values from a provided data set (simple bootstrapping) or based upon a known distribution for each data set (parametric bootstrapping). The range of the input variables is defined by the data gathered for each individual bridge deck.

After the time required for corrosion to initiate has been calculated the time to corrosion cracking must be added. The time for cracking to initiate plus the time to crack propagation was calculated using two models (Liu and Weyers, 1998 and Vu, Steward, and Mullard, 2005). The Liu/Weyers model was used to predict the time to crack initiation while the Vu, Stewart, and Mullard model was used to predict the time required for the crack to propagate to a limit state. The values for the parameters used were selected to represent the characteristics of a typical bridge deck in Virginia.

The corrosion initiation concentration values (C_{init}) that were used to estimate the service life of the bridge decks were developed from experimental results that were obtained from corrosion testing carried out on bridge deck cores (Brown, 2002). The initiation values reasonably agree with a triangular distribution with a minimum of 0.66 lbs/CY (0.39 kg/m^3) and a maximum of 10.6 lbs/CY (6.26 kg/m^3). The distribution is skewed to the left with an estimated mode of 2.37 lbs/CY (1.4 kg/m^3). Using the parameters obtained from Brown’s research a set of 20000 initiation values was randomly generated for use as input to the service life model. Twenty thousand values were generated in order to completely define the distribution. It was found that the actual number of values generated will not significantly affect the time to corrosion initiation estimations as long as a minimum of 2000 values are used. Also, the corrosion threshold distribution varies depending on the type of steel.

The D_{ca} values that were determined from the sampled bridge deck cores were normalized to an age of 35 years. The normalized values were then used in the service life estimations. The C_o values used in the service life model were the measured values taken from the deck cores at a depth of ½ in minus the estimated background chloride concentration. In instances where the chloride concentration reached a maximum at a depth greater than ½ in the higher concentration was used for C_o. The cover depths determined from the pachometer measurements were used as the input to the service life model.

Life Cycle Cost Analysis

The total cost of a bridge deck includes construction, maintenance, repair and rehabilitation of the deck throughout its’ service life. Many alternatives are available for maintaining a bridge deck, with different costs and timings associated with each. To assist in the comparison of alternatives an approach referred to as Life-Cycle Cost Analysis (LCCA) was used. LCCA as related to bridges can be defined as "a set of economic principles and computational procedures for comparing initial and future costs to arrive at the most economical strategy for ensuring that a bridge will provide the services for which it was intended" (Hawk, 2003). LCCA was separated into the five basic steps listed below:

1. Establish design alternatives
2. Determine activity timing
3. Estimate costs (agency and user)
4. Compute life-cycle costs
5. Analyze the results

Multiple maintenance alternatives were analyzed to determine the optimum maintenance strategy for these in-place bridge decks. The LCCA was based on a service life of 100 years and a base year of 2008. A base year of 2008 was selected because it is anticipated that 2008 will be the earliest possible time of implementation for the project. LCC comparisons were based upon computed unit costs ($/SY).

Bridge deck LCCAs were conducted for two possible repair/rehabilitation alternatives for preventing/repairing corrosion related deterioration. The initial condition of the bridge decks compared were considered equivalent. Therefore, the only differences in the LCCA alternatives were related to the maintenance procedures. The two deck maintenance alternatives that were investigated were polymer overlays and concrete overlays. The timings of the alternatives represent those timings associated with a bridge deck that has a current deterioration level between 0 and 1%. Year zero does not represent the time at which the bridge deck is put in place but rather the time of analysis.

The next step in conducting the LCCA was to determine the costs associated with each maintenance alternative. All maintenance expenditures were adjusted to reflect their estimated costs in 2008. The costs were estimated using tabulated VDOT bid data from 1997, 1999, and 2004. The average inflation rate was determined for each bid item for the time period of 1997 – 2004. Using the 2004 cost data and the average inflation rate the costs were projected for the year 2008. A discount rate of 5.1% was used.

Results

The service life of Virginia concrete bridge decks is generally controlled by chloride-induced corrosion of the reinforcing steel as a result of the application of winter maintenance deicing salts. A chloride corrosion model accounting for the variable input parameters using Monte Carlo resampling was developed. The model was validated using condition surveys from 10 Virginia Bridge decks built with bare steel. The influence of changes in construction specifications of w/c = 0.47 and 0.45 and w/cm = 0.45 and cover depth increase from 2 to 2.75 inches were determined. The 0.45 $^{w}/_{c}$ bridge decks reflected little to no damage due to their young age relative to the older 0.47 $^{w}/_{c}$ bridge decks. The C_o values demonstrate the similarities between the three deck sets. The average cover depths are generally higher for the 0.45 $^{w}/_{c}$ bridge deck sets. This is due to the VDOT specification change of an increase in cover depth that coincided with the decrease in the $^{w}/_{c}$ from 0.47 to 0.45. In general, there was little difference between D_{ca} values normalized to age 35 years and the average calculated values for the age at sampling.

Histograms of the input data were developed for each of the three bridge deck sets to investigate the distributions of the input parameters. The histograms indicate that C_o, and D_c may be reasonably described by the gamma distribution while cover depths follow a normal distribution which is in agreement with previous studies (Pyc, 1998, Zemajtis, 1998, Kirkpatrick, 2001).

LCC comparison tables were developed for decks where a maintenance strategy may be selected within the next 50 years in 10-year intervals. The tables are presented with and without traffic control costs and without user costs. Where bridge maintenance decisions are to be made in years other than those presented in the tables, the LCCs may be approximated by a linear interpolation between adjacent 10 year periods.

Using the cash flow diagram presented in the report, the engineer can investigate the effects of varying traffic volumes on the selection of the appropriate maintenance strategy. Polymer overlays are the most economical option in nearly all cases. Concrete overlays are more cost-effective only if the ADT is expected to be very high and the required remaining service life falls within certain time frames.

Conclusions

The project conclusions are as follows:

- The time to first repair and rehabilitation of bridge decks can be modeled using a probabilistic approach, which allows for the incorporation of variability related to chloride exposure conditions, bridge deck construction, and corrosion initiation.

- Fick's second law of diffusion can be used to model the apparent diffusion rate of chlorides into a concrete bridge deck. Additionally, the effective diffusion rate at any point in time can be projected using available diffusion decay models.

- The time required for corrosion to induce cracking in the cover concrete can be estimated using existing corrosion-cracking models. An estimated time to corrosion cracking of 6 years for bare steel reinforcement was determined for this study.

- A reasonable estimate of the time required for corrosion deterioration to progress from a level of 2% to a level of 12% was determined from damage surveys conducted on actively corroding bridge decks. The corrosion propagation time for bare steel bridge decks is estimated to be 16 years.

- The reduction of the $^{w}/_{c}$ ratio from 0.47 to 0.45 appears to have a negligible effect on the diffusion properties of the sampled bridge deck concrete.

- The addition of fly ash or slag to the sampled bridge deck concrete mixture appears to dramatically reduce the diffusion rate of chlorides into concrete and have equivalent long term corrosion protection effects.

- The service lives of bridge decks constructed under current specifications (0.45 $^{w}/_{cm}$ and 2 in cover depth) are expected to exceed a design life of 100 years regardless of reinforcement type.

- Surface chloride concentrations, C_o, have been determined for the Commonwealth of Virginia and are only a function of the environmental exposure conditions not the type of concrete.

- Apparent diffusions, D_{ca}, have been determined for the Commonwealth of Virginia for $^{w}/_{c} = 0.47$, $^{w}/_{c} = 0.45$ and $^{w}/_{cm} = 0.45$ bridge deck concrete and may be used in estimating the rate of corrosion damage to bridge decks within the Commonwealth of Virginia.

- The rate of deterioration of populations of bridge decks built under different state wide specifications may be determined using the probability based chloride diffusion model, plus the time to cracking of 6 years, plus the propagation period of 16 years for 2% to 12% damage of the worst span lane.

- The diffusion model plus the time to cracking and propagation periods may be used to predict the rate of corrosion damage for individual decks provided sufficient input data is provided. Model data requirements are provided in the recommendations section of the report.

- Life Cycle Costs Analyses can be conducted to determine optimum maintenance strategies for individual bridge decks.

- It is not appropriate to specify a single maintenance strategy for all bridge decks within a system, as the most economical alternative will be dependent upon individual structure parameters.

- Long-term inflation rates associated with transportation-related construction appear to correspond with the inflation rate of the general economy.

- A total maintenance cost approach to maintenance strategy selection generally results in the same conclusions as a LCCA approach.

Recommendations

The following recommendations are to be addressed by VDOT's Structures & Bridge Division:

- It is recommended that newly constructed bridge decks be built under current specifications with bare steel reinforcement. The decision to use bare steel reinforcement over available alternative reinforcements was made based upon the determination that the service lives of bridge decks constructed under current cover depth and low permeable concrete specifications are expected to exceed 100 years regardless of reinforcement type. Therefore, reinforcement type should be selected on a first-cost basis. Bare steel being the least costly alternative would typically be the reinforcement of choice. However, alternative reinforcements such as stainless steel, stainless steel clad, or MMFX-2 may be used in place of bare steel as a secondary corrosion protection method for extreme chloride exposures or where a redundant corrosion protection system is required by FHWA.

- Life Cycle Cost Analyses should be conducted to determine the most economical maintenance alternative for individual bridge decks. Real discount rates provided by the Office of Management and Budget should be used to discount future expenditures (OMB, 2007). It is also recommended that the engineer account for costs incurred by the traveling public (User costs) as well as Agency costs in order to provide the most economical alternative to the public as a whole.

- The probability based chloride deterioration model and its associated computer software is to be used to determine the rate of corrosion damage of bridge decks. Polymer concrete overlays may be scheduled when the damage level is predicted to be between 0.5 and 1% damage. Otherwise, a concrete overlay is to be scheduled when the damage level of the worst span lane is between 10 and 12%.

- The chloride diffusion coefficients, D_{ca}, presented in Appendix A may be used in the probability model computer program for concrete bridge decks built with w/c = 0.47, w/c = 0.45, and w/cm = 0.45. Should more exact values be needed, the following sampling rate is recommended.

  Number of D_{ca} values = 20 + (L-150/7) Equation 5

  Where:
  L = length of the bridge deck in feet.

  A minimum of 5 chloride concentrations at various depths, including the surface chloride concentration, Co, are required to determine the apparent diffusion coefficient using the computer program. An additional value is needed to determine the chloride background concentration. A depth of 3 to 4 inches is normally sufficient for the background chloride concentration. Background values are to be subtracted from the 5 chloride concentrations values at various depths prior to calculating the diffusion coefficient.

- Service life estimates of specific bridge decks require cover depth measurements and surface chloride concentrations. The number of surface chloride concentrations is to be determined using equation 5. Surface chloride samples are to be from 0.25 to 0.75

in below the surface of the bridge deck concrete. The number of cover depth measurements are to be determined as follows:

Number of cover depths = 40 + (L-20/3) Equation 6

- Measurements and samples are to be taken from the critical failure zone of the bridge deck and equally distributed throughout the length of the deck in non-damaged areas. Critical failure zone is typically the right traffic lane wheel path areas. Damage is defined as spalled, delaminated, and patch areas (asphalt or concrete). Thus, a damage condition survey is to be performed prior to cover depth measurements and chloride sampling.

- At least one 4 inch diameter core, 4 to 5 inches in length and not containing any reinforcing is to be taken for petrographic analysis to determine if the concrete contains fly ash or slag.

Costs and Benefits

The cost to implement the recommendations is variable depending on the bridge deck size and location. For an average bridge deck, 200 feet long and 40 feet wide, a two person crew can complete the field survey work in one day. Laboratory work, petrographic analysis of one core would be about $200 dollars and each powdered chloride concentration measurement is about $75.00. Thus, for an average bridge deck where only the surface chloride concentrations are needed, the total laboratory cost would be $2025.00. The two-person crew for one day would be about $1,440.00. Computer and engineering time is estimated at 2 hours or about $300.00. Thus, the total cost per average bridge deck is estimated at $3,665.00 plus travel expenses and traffic control.

Benefits are as follows:

- Cost savings to VDOT through optimum scheduling of bridge deck maintenance work.

- Cost savings to VDOT through the optimum selection of polymer concrete and concrete overlay maintenance work.

- Cost savings to users through minimizing delays and accidents.

INTRODUCTION

Virginia has 10,120 bridges on the National Bridge Inventory (NBI) and 2,871 non NBI bridges and thus over 100 million square feet of bridge deck. In 2006, Virginia Department of Transportation (VDOT) deck expenditures were about $7.9 million on 11,857 decks maintained by VDOT. Approximately 1.5 million square feet of bridge deck is added to the Commonwealth's inventory annually. The primary deck construction material is reinforced concrete. Winter maintenance applications of deicer salts result in the spalling of the cover concrete and subsequent deterioration of ride quality and safety.

Bridge decks represent the severest exposure conditions of bridge components. Decks are directly exposed to temperature and precipitation changes, application of deicing salts, and abrading traffic forces. Bridge deck exposure conditions are highly variable throughout the Commonwealth. Average daily traffic varies from in the hundreds to over 90,000 vehicles a day. Severity of winter conditions varies significantly from the mild Tidewater area to the severe Southern Mountain region.

Over a period of three winters, 2000-01, 2001-02, and 2002-03, the average application of chloride tons per lane-mile for the six Virginia climatic zones were:

- Western Piedmont 0.39
- Tidewater 0.40
- Eastern Piedmont 0.94
- Central Mountains 1.18
- Southern Mountains 1.22
- Northern 7.75

The above chloride exposures represent not only the severity of winter conditions but also district winter maintenance operations in frequency, method, and type of deicing salt. For example, the Northern Virginia District used both sodium and magnesium chloride, the magnesium chloride results in the application of two chlorides versus one for sodium chloride; whereas, the other eight districts primarily used sodium chloride.

Bridge deck exposure to deicing chemicals is not only highly variable within the Commonwealth but also variable within a climatic zone and engineering district. Thus, there is pressing need to estimate the service life of bridge decks in order to prioritize maintenance dollars and thus maximize cost efficiency of maintaining Virginia bridge decks at an acceptable level of service.

Service life models are a critical part of cost efficiency. For concrete bridge decks in chloride laden environments, as Virginia, service life models may be used to estimate the remaining years to maintenance and rehabilitation of existing concrete bridge decks. Also, to select the most cost effective corrosion protection system for new construction in various exposure conditions. Service lives coupled with life cycle cost analyses provide the means of maximizing the cost efficiency of maintaining the Commonwealth's transportation system.

PURPOSE AND SCOPE

The purpose of the project consisted of two distinct phases, service life estimates of concrete bridge decks and the cost of maintaining concrete bridge decks for 100 years. With respect to service life estimates, a probability based chloride corrosion service life model was used to estimate the service life of bridge decks built under different concrete and cover depth specifications between 1969 and 1971 and 1987 and 1991. In addition, the influence of using alternative reinforcing steel as a secondary corrosion protection method was evaluated. Life cycle costs were estimated for maintaining bridge decks for 100 years considering the present age of the deck. Life cycle costs were estimated using both present worth and considering the inflated costs VDOT would expend to maintain concrete decks.

The scope of the service life estimates was limited to the validation of the probability based model using field survey data of 10 bridge decks built with bare steel. Later age decks consisted of 16 decks built with a w/c = 0.45 and 11 decks built with a w/cm = 0.45. The supplemental cement materials were either slag or fly ash. Alternative reinforcing steels considered were galvanized steel, MMFX-2, and stainless steel. Epoxy coated reinforcing steel was not included in the selection of alternative reinforcing steels because over 15 years of continuous research has demonstrated that epoxy coated reinforcing steel corrosion protection performance is at best marginal, providing about 5 years additional corrosion resistance in field structures (Weyers, Brown and Sprinkel, 2006). Cost to maintain concrete bridge decks for 100 years considered VDOT primary maintenance method, polymer overlays and rehabilitation method, concrete overlays either micro-silica or latex-modified concrete.

METHODS AND MATERIALS

Bridge Deck Selection

The research plan called for the survey of 40 bridge decks. The distribution of bridge deck types was to be as follows: 10 bare steel with $^{w}/_{c}$ = 0.47, 15 with $^{w}/_{c}$ = 0.45 and 15 with $^{w}/_{cm}$ = 0.45. VDOT officials compiled a list of potential bridge decks that indicated whether or not fly ash or slag were used in the deck concrete, the type of reinforcement and the age of the structure. Of the 40 decks, 37 were surveyed. Three decks were not surveyed because of traffic safety constraints. Additionally, the decks selected for surveying were evenly dispersed across the 6 climatic zones in Virginia. The bridge locations are presented in Figure 1.

Core samples from the decks were used to confirm the composition of the concrete. The final distribution of deck types sampled was as follows: 10 bare steel with $^{w}/_{c}$ = 0.47, 16 with $^{w}/_{c}$ = 0.45 and 11 with $^{w}/_{cm}$ = 0.45. A list of bridge decks surveyed is presented in Table 1.

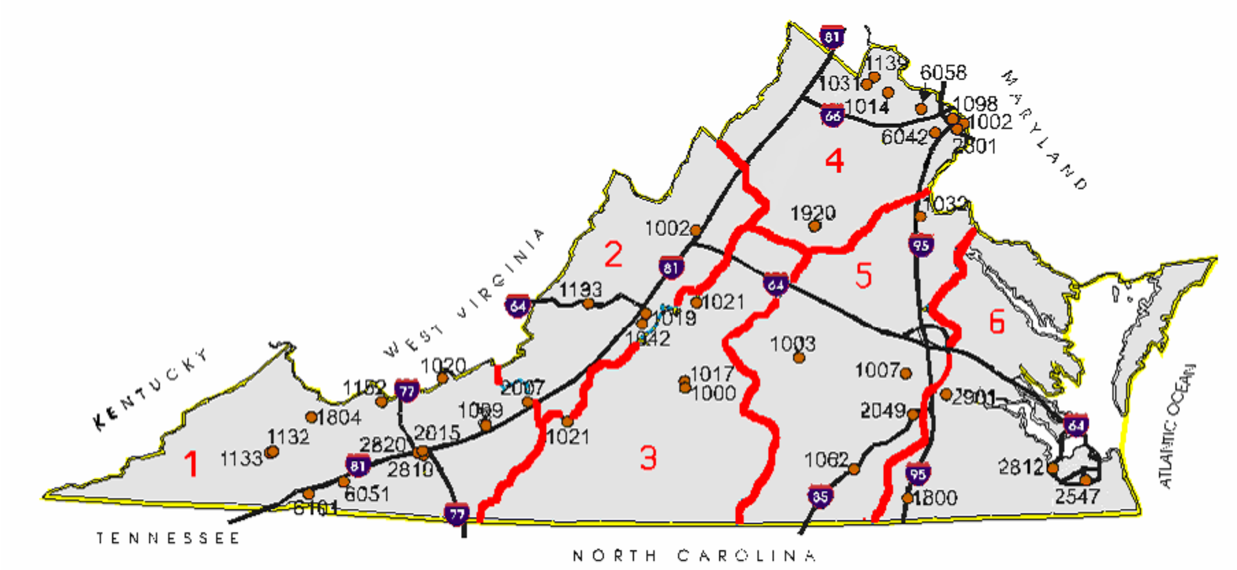

Figure 1. Surveyed Bridge Locations

Deck Survey

Bridge deck rehabilitation decisions are based upon the deterioration of the worst-span-lane of the deck. The right-hand lane normally receives more traffic and therefore deteriorates at a faster rate. For that reason, and due to safety and traffic control issues, only the right-hand lanes were surveyed. The deck survey included a visual survey, non-destructive testing, and the collection of 15 - 4 in concrete cores per deck.

Visual Survey

The following data were gathered for each bridge deck during the visual survey:

- The length and width of the right traffic lane were measured.
- Patched areas within the right-hand lane were measured and recorded.

Non-destructive Field Testing

The following non-destructive tests were conducted during the field survey:

- Cover depth determinations for the top mat of reinforcing steel. 40-80 measurements were taken per span at 4-foot intervals in the wheel paths using a Profometer 3 cover depth meter. If the span length did not allow for 40 measurements to be taken at 4-foot intervals the interval was reduced to 2 feet.

- The right-hand lane was sounded using the chain drag method to determine delaminated areas.

Table 1. Bridges Surveyed

District	County	Structure Number	Year Built	Age at survey (years)	Climatic Zone	Reinforcement Type	Specified Concrete
1	Tazwell	1804	1969	34	1 (SM)	Bare	0.47 w/c
1	Washington	6101	1969	34	1 (SM)	Bare	0.47 w/c
2	Montgomery	2007	1970	33	1 (SM)	Bare	0.47 w/c
3	Nelson	1021	1971	32	3 (WP)	Bare	0.47 w/c
4	Brunswick	1062	1969	34	5 (EP)	Bare	0.47 w/c
4	Dinwiddie	2049	1968	35	5 (EP)	Bare	0.47 w/c
5	Emporia	1800	1970	33	6 (TW)	Bare	0.47 w/c
6	Stafford	1032	1971	32	6 (TW)	Bare	0.47 w/c
9	Alexandria	2801	1970	33	4 (N)	Bare	0.47 w/c
9	Fairfax	6042	1969	34	4 (N)	Bare	0.47 w/c
1	Russell	1132	1988	15	1 (SM)	ECR	0.45 w/c
1	Russell	1133	1988	15	1 (SM)	ECR	0.45 w/c
1	Wytheville	2820	1986	17	1 (SM)	ECR	0.45 w/c
1	Smyth	6051	1990	13	1 (SM)	ECR	0.45 w/c
2	Giles	1020	1986	17	1 (SM)	ECR	0.45 w/c
3	Cumberland	1003	1988	15	5 (EP)	ECR	0.45 w/c
4	Chesterfield	1007	1990	13	5 (EP)	ECR	0.45 w/c
4	Prince George	2901	1991	12	5 (EP)	ECR	0.45 w/c
5	Chesapeake	2547	1984	19	5 (EP)	ECR	0.45 w/c
7	Orange	1920	1991	12	4 (N)	ECR	0.45 w/c
8	Rockbridge	1019	1984	19	2 (CM)	ECR	0.45 w/c
8	Allegheny	1133	1987	16	2 (CM)	ECR	0.45 w/c
9	Loudoun	1014	1987	16	4 (N)	ECR	0.45 w/c
9	Loudoun	1031	1990	13	4 (N)	ECR	0.45 w/c
9	Arlington	1098	1988	15	4 (N)	ECR	0.45 w/c
9	Loudoun	1139	1987	16	4 (N)	ECR	0.45 w/c
1	Tazewell	1152	1987	16	1 (SM)	ECR	0.45 w/cm
1	Wytheville	2815	1986	17	1 (SM)	ECR	0.45 w/cm
1	Wytheville	2819	1986	17	1 (SM)	ECR	0.45 w/cm
2	Franklin	1021	1988	15	3 (WP)	ECR	0.45 w/cm
3	Campbell	1000	1991	12	3 (WP)	ECR	0.45 w/cm
3	Campbell	1017	1990	13	3 (WP)	ECR	0.45 w/cm
5	Suffolk	2812	1991	12	6 (TW)	ECR	0.45 w/cm
8	Augusta	1002	1988	15	2 (CM)	ECR	0.45 w/cm
8	Rockbridge	1042	1990	13	2 (CM)	ECR	0.45 w/cm
9	Arlington	1002	1987	16	4 (N)	ECR	0.45 w/cm
9	Fairfax	6058	1991	12	4 (N)	ECR	0.45 w/cm

Deck Cores and Laboratory Testing

The concrete cores were taken within the wheel paths on the deck as that is the critical deterioration area. Three of the cores were taken for petrographic analysis purposes and did not contain reinforcing steel. Of the remaining 12, all contained reinforcing steel and 3 were taken directly over cracks in the deck. After the cores were removed the water on the surface resulting from the coring process was allowed to evaporate. The cores were then wrapped in two layers of 4-mil polyethylene and one layer of aluminum foil. The cores were then wrapped in a protective layer of duct tape to preserve the in-place moisture content of the concrete samples until they could be analyzed in the lab.

The following tests were conducted in the laboratory on the cores taken from the bridge decks:

- Chloride concentrations were determined in accordance to ASTM C 1152-97 at the following seven depths for each concrete core sample: 0.5 in, 0.75 in, 1.0 in, 1.25 in, 1.5 in, at the depth of the reinforcement, and below the reinforcement.

Service Life

Chloride titration data for diffusion constant (D_{ca}) and surface concentration (C_o), cover depth measurements, and the deck damage survey were used to estimate service lives.

The estimates of service life of a bridge deck consists of three distinct time periods, see Figure 2.

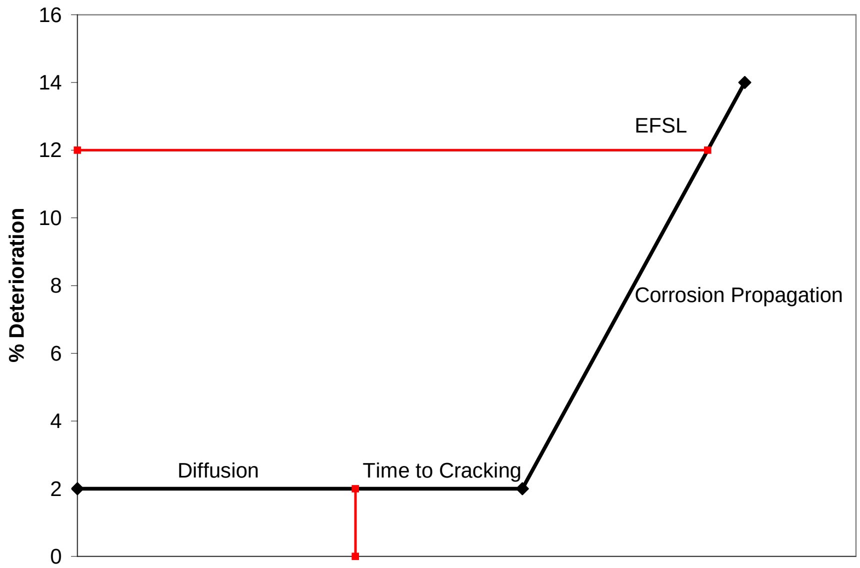

Figure 2. Service Life Model

1. Time to corrosion initiation,
2. Time from initiation to cracking, and
3. Time for corrosion damage to propagate to a limit state

The time period for corrosion initiation in this study is the time required for the chloride initiation concentration to be reached at 2% of the bridge deck reinforcing steel. The initiation of corrosion up to 2% of the bridge deck reinforcing steel can be modeled using basic Fickian diffusion behavior. Predictions beyond the 2% initiation level are potentially misleading due to the way that corrosion propagates throughout a bridge deck. As areas of reinforcement begin to actively corrode, other areas of reinforcement will become cathodic. Cathodic areas may remain cathodic even at high chloride concentrations. Additionally, corrosion at the anodic sites will eventually cause the concrete cover to crack, which will allow for the rapid ingress of chlorides. The increase in chlorides at the corroding site will accelerate corrosion in that area and in adjacent areas.

Once corrosion has initiated on 2% of the reinforcing steel corrosion will progress until the cover concrete cracks and the deterioration becomes visually evident. The time to cracking will be estimated using the corrosion cracking models.

The total corrosion propagation time is the time required for corrosion deterioration to advance from a level of 2% to a level of 12%. A damage level of 12% connotes the End of Functional Service Life (EFSL) for a bridge deck as demonstrated by a survey of DOT officials (Fitch, Weyers, and Johnson, 1995). Damage is defined as the sum of the patched, spalled, and delaminated areas. Modeling the propagation of corrosion from 2% to 12% damage was achieved by measuring the additional damage that had taken place in 3 years from the initial survey of the w/c = 0.47 decks.

The service life software used for this project, Bridge Corrosion Analysis (BCA), models the diffusion of chlorides using simple Fickian behavior with time-independent input parameters. The model simplifies the diffusion process to the extent that it can be easily used as a bridge engineering and management tool. A Fickian based diffusion model was used to allow for the easy incorporation of the stochastic nature of the input variables. BCA was developed as an Excel module, which was added to the standard Microsoft Office package.

Probabilistic Service Life Models

Service life models can be either deterministic or probabilistic. Deterministic service life models estimate the EFSL for a bridge deck using an average value for the various input parameters. Conversely, probabilistic models incorporate the stochastic nature of the variables into service life estimates. Previous research concerning the service life modeling of bridge decks has shown that a deterministic approach significantly over estimates service life (Kirkpatrick, 2001). The software used in this project uses a Monte Carlo statistical resampling technique to allow for the integration of input parameter variability into the model.

Monte Carlo Simulation (MCS) is defined as “any method, which solves a problem by generating suitable random numbers and observing that fraction of the numbers obeying some property or properties” (Weisstein, 2006). MCS takes into account the statistical nature of the input parameters by randomly selecting numerical values from a provided data set (simple bootstrapping) or based upon a known distribution for each data set (parametric bootstrapping). The range of the input variables is defined by the data gathered for each individual bridge deck. It is also important to ensure that the number of sampling iterations used is adequate. It has been shown that for 10,000 iterations the service life prediction will converge to a near constant value when the distributions of the input variables are adequately defined (Kirkpatrick, 2001).

Time to Corrosion Initiation

The first step in estimating the time to corrosion initiation is calculating D_{ca} from the chloride profiles developed from the bridge deck samples. D_{ca} is calculated using Fick's second law of diffusion.

$$C_{(x,t)} = C_o\left(1 - \operatorname{erf}\frac{x}{2\sqrt{Dct}}\right) \qquad \text{Equation 1.}$$

Where:

$C_{(x,t)}$ = chloride concentration at depth x and time t,
C_o = surface chloride concentration
D_{ca} = apparent diffusion coefficient
t = diffusion time
x = depth, and
erf = statistical error function

The diffusion model back calculates D_{ca} using chloride concentration data obtained from the concrete samples taken from the bridge decks. The surface chloride concentration is an important factor in calculating D_{ca}. It has been shown that the chloride concentration profiles for bridge deck cores reach a maximum at a depth of approximately ½ in after 5 – 10 years of exposure to deicing salts (Weyers et al., 1992), due to the propensity for chlorides to be washed out of the surface of the deck resulting in lower concentrations at the surface than at a depth just below the surface. Thus, it is necessary to use the chloride concentration at a depth of ½ in as the C_o.

Using the chloride concentrations at various depths determined from the laboratory data, D_{ca} is calculated using a least sum of the squared error curve fitting analysis of Equation 1. The chloride profiles represent the measured chloride concentrations less a predetermined background chloride concentration. The calculated apparent diffusion coefficients are used as input to the service life model. The measured surface concentrations and cover depths are also used to define the sample set of their corresponding model variables.

Chlorides initially present within a concrete mixture either contained within the cement paste or the aggregate are known as background chlorides. The concentration of background chlorides is relatively uniform and varies between bridge decks, but is in general relatively low in Virginia.

The background chloride concentration was calculated to be the average of the chloride concentrations taken from below the reinforcement. The background chloride concentration was then subtracted from each chloride profile prior to the determination of D_{ca}. Background concentrations were determined for each bridge deck independently, as it is not uncommon for different concrete mixtures to have significantly different background chloride concentrations.

The three referenced equations which have the same form and differ little were used to model the decay of D_c over time. However, the diffusion coefficients that are calculated from the field data are the apparent diffusion coefficients (D_{ca}) not the actual diffusion coefficients for the concrete at the time of sampling. D_{ca} can be defined as the average actual diffusion coefficient (D_c) value over the life of a structure. Therefore, D_{ca} will have a higher value than D_c at any given point in time with the margin of difference between D_{ca} and D_c decreasing with time.

Adjusting Diffusion Coefficients for Time Dependency

The diffusion properties of concrete are time-dependent. To account for time effects in the measured D_{ca} values three diffusion models were used to estimate the decay of D_c over time (Mangat and Molly, 1994, Bamforth, 1999, and Thomas and Bentz, 2000).

Using the three diffusion decay models the D_{ca} functions may be forced to fit through a known measured value at a specified time and then the actual D_c can be calculated for that particular sample at any time in the past or a prediction can be made for the future value of D_c. As an example, the diffusion comparison presented in Figure 3 for the Life – 365 model was determined using a known D_{ca} value of 0.009 in^2/yr (6.0 mm^2/yr) at an age of 12 years. The procedure used to generate the diffusion decay plot is as follows:

1) A random initial D_c value was selected and the diffusion curve was generated based upon that value and the value for m that was selected based upon the concrete mixture proportions.
2) The D_{ca} diffusion curve was then generated by averaging the D_c values over the life of the structure.
3) The D_{ca} curve was then checked to ensure that it passed through the known point of 0.009 in^2/yr (6.0 mm^2/yr) at an age of 12 years.
4) If the D_{ca} curve does not pass through the known point a new value for the initial D_c would be selected and the process repeated. Figure 3 represents the final iteration.

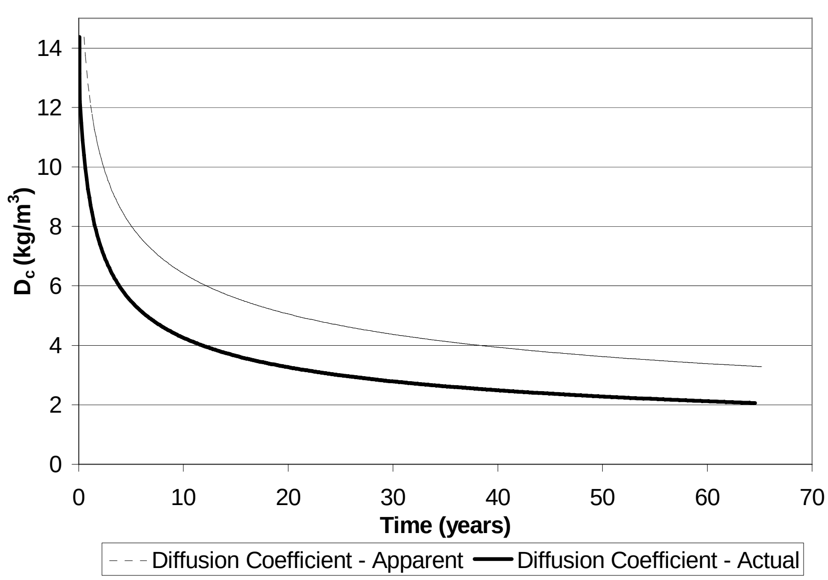

Figure 3. Diffusion Decay – Life – 365

The process was completed for each individual bridge deck and also for each of the three sets of bridge decks. The slopes of the apparent D_c curves have been shown to decrease linearly at a relatively slow rate after approximately 35 years. Thus, it was deemed appropriate to use the 35-year values as input values for the service life model.

BCA Service Life Model

The BCA service life model uses Monte Carlo Simulation to calculate the time required for a given bridge deck to reach a 2% level of corrosion initiation. The input form for the service life calculation is presented in Figure 4.

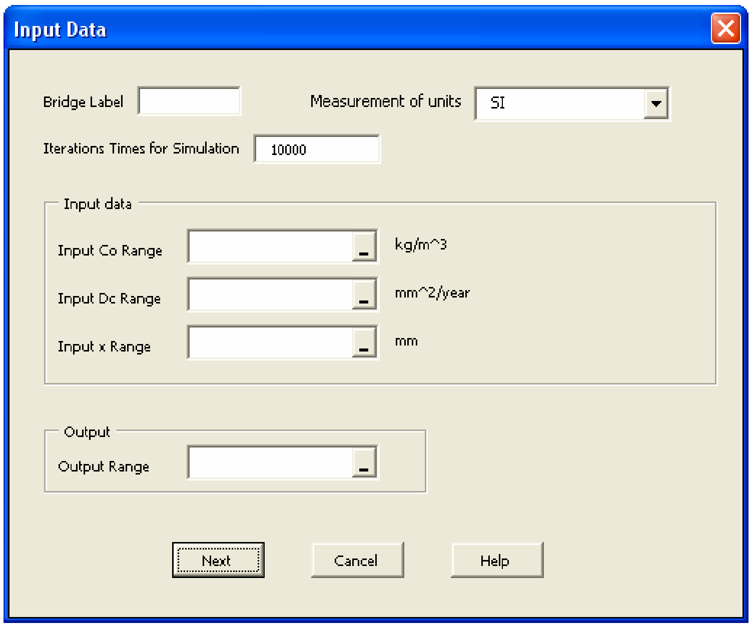

Figure 4. BCA Chloride Threshold Input Form

BCA accepts a set of input values from which it will randomly select a value for each variable using the simple bootstrapping method. Once the necessary input data has been provided, the program will prompt the user for information regarding the chloride threshold concentrations. The chloride threshold input form is presented in Figure 5.

The chloride threshold values that may be used in the service life calculation can be specified in one of four ways.

1) Default values for 5 different corrosion protection methods can be used that are specified by BCA,
2) User can specify minimum, maximum, and mode values for the chloride threshold and BCA will generate values according to a triangular distribution,
3) User can specify a mean and standard deviation of the threshold values and BCA will generate values according to a normal distribution, or
4) User can specify a set of threshold values and BCA will sample directly from that set.

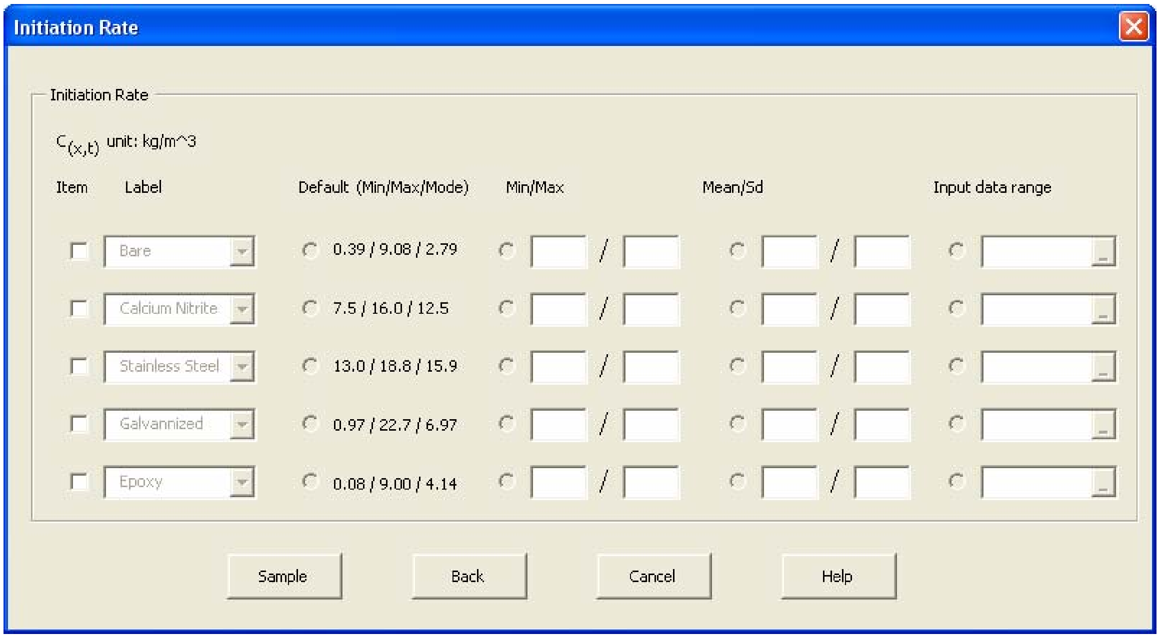

Figure 5. BCA GUI – Service Life Input Form

The first three options use parametric bootstrapping to generate and select chloride threshold values from the distributions while the fourth method uses simple bootstrapping to sample directly from a provided data set. After the chloride threshold information has been provided

BCA will calculate the time required for corrosion to initiate for that set of input values and chloride thresholds. The process is repeated for the number of specified iterations up to a maximum of 65000 iterations. The computer routine that is used is illustrated in Figure 6. A Cumulative Distribution Function (CDF) is then generated using the calculated corrosion initiation times and the time required for 2% of the reinforcing steel to initiate corrosion can then be estimated.

Time to Corrosion Cracking for Bare Steel

After the time required for corrosion to initiate has been calculated the time to corrosion cracking must be added. The time for cracking to initiate plus the time to crack propagation was calculated using two models (Liu and Weyers, 1998 and Vu, Steward, and Mullard, 2005). The values for the parameters used were selected to represent the characteristics of a typical bridge deck in Virginia as follows:

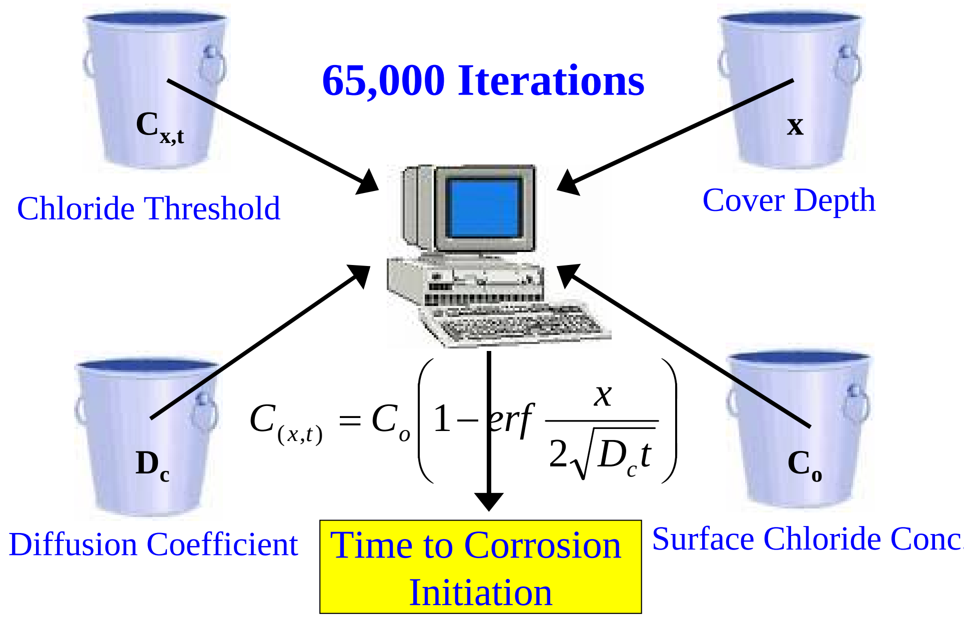

Figure 6. BCA Service Life Estimation Routine

Parameters (Liu/Weyers):

C = 2.056 in (52.2 mm)	D = 0.62 in (15.875 mm)	d_o = 0.0005 in (0.0125 mm)
f'_t = 478.6 psi (3.3 Mpa)	E_{ef} = 1035.3 ksi (9000 Mpa)	i_{corr} = 2 mA/ft^2
ν_c = 0.18	α = 0.523 – 0.622	ρ_{st} = 490.7 pcf (7.86 mg/mm^3)
ρ_{rust} = 224.7 pcf (3.6 mg/mm^3)		

Parameters (Vu, Steward, Mullard):

A = 62, 225, 700	B = 0.45, 0.29, 0.23	C = 2.056 in (52.2 mm)
$^w/_c$ = 0.45	$i_{corr(exp)}$ = 100 mA/ft^2	$i_{corr(real)}$ = 2.14 mA/ft^2
α = 0.85	β = -0.3	Crack width = 0.01 – 0.04 in (0.3 – 1.0 mm)

The Liu/Weyers model was used to predict the time to crack initiation while the Vu, Stewart, and Mullard model was used to predict the time required for the crack to propagate to a limit state.

The corrosion products were taken to be a composition of $Fe(OH)_3$ and $Fe(OH)_2$ and the crack width limit state was taken to be 0.01 in (0.3 mm). A crack width limit state of 0.01 in (0.3 mm) was selected because it has been suggested that crack widths of less than 0.01 in (0.3 mm) have little to no effect on the ingress of chlorides into the concrete (Atimay and Ferguson, 1974). Using these parameters the time to crack initiation was calculated to be 2.40 years and the time for crack propagation was calculated to be 3.42 years yielding a total corrosion cracking propagation time of 5.82 years. For simplicity the total crack propagation time that will be used to estimate bridge deck service life is 6 years.

Estimating the Propagation Time of Corrosion for Bare Steel Bridge Decks

The propagation of corrosion is a complex process that cannot be described by simple Fickian behavior. BCA is not currently capable of determining the propagation period. Therefore, the corrosion propagation time has been estimated using empirical data.

To estimate the corrosion propagation time for bare steel bridge decks in Virginia those bridge decks that reflected the most damage during the initial survey were resurveyed three years later. A total of 7 bridge decks were resurveyed and their effective deterioration rates calculated. It was found that the deterioration rate of a bridge deck is related to the amount of initial damage on that deck.

A regression analysis was used to estimate the required amount of time for corrosion to propagate from a level of 2% to a level of 12%. The resulting plot is presented in Figure 7 below reflecting an estimated total propagation time of approximately 16 years, for damage to propagate from 2% to 12% damage.

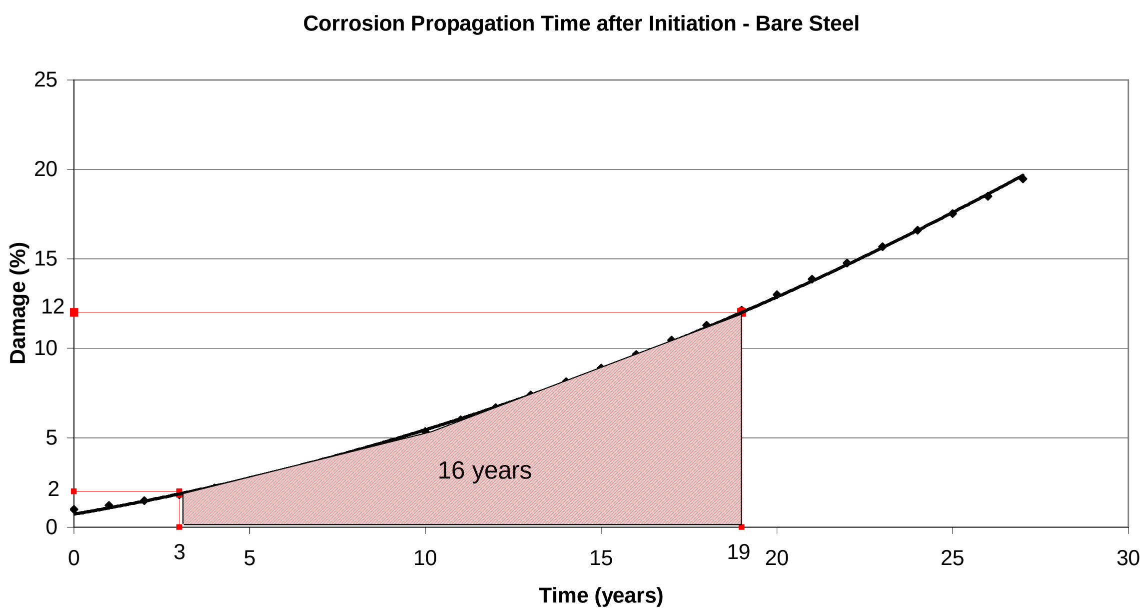

Figure 7. Total Propagation Time

The time required to reach a specific level of deterioration can also be calculated using the following equation:

$$TimeToDeterioration = 8.61\left(\sqrt{\%Deterioration + 1.38} - 1.45\right) - 3.34 \qquad \text{Equation 2}$$

The time calculated will be the time for corrosion to progress from a deterioration level of 2% to the specified level.

Corrosion Initiation Concentrations

The corrosion initiation concentration values (C_{init}) that were used to estimate the service life of the bridge decks were developed from experimental results that were obtained from corrosion testing carried out on bridge deck cores (Brown, 2002). The estimated corrosion initiation concentrations are presented in Figure 8.

The initiation values reasonably agree with a triangular distribution with a minimum of 0.66 lbs/CY (0.39 kg/m^3) and a maximum of 10.6 lbs/CY (6.26 kg/m^3). The distribution is skewed to the left with an estimated mode of 2.37 lbs/CY (1.4 kg/m^3). The range of initiation values is in general agreement with values reported in the literature (Stratfull et al., 1975; Vassie, 1984; Matsushima et al., 1998; Henriksen, 1993). A comprehensive review of corrosion initiation concentrations values ranging from 1.0 – 14.83 lbs/CY (0.59 – 8.75 kg/m^3) were reported (Glass and Buenfeld, 1997). Using the parameters obtained from Brown's research a set of 20000 initiation values was randomly generated for use as input to the service life model.

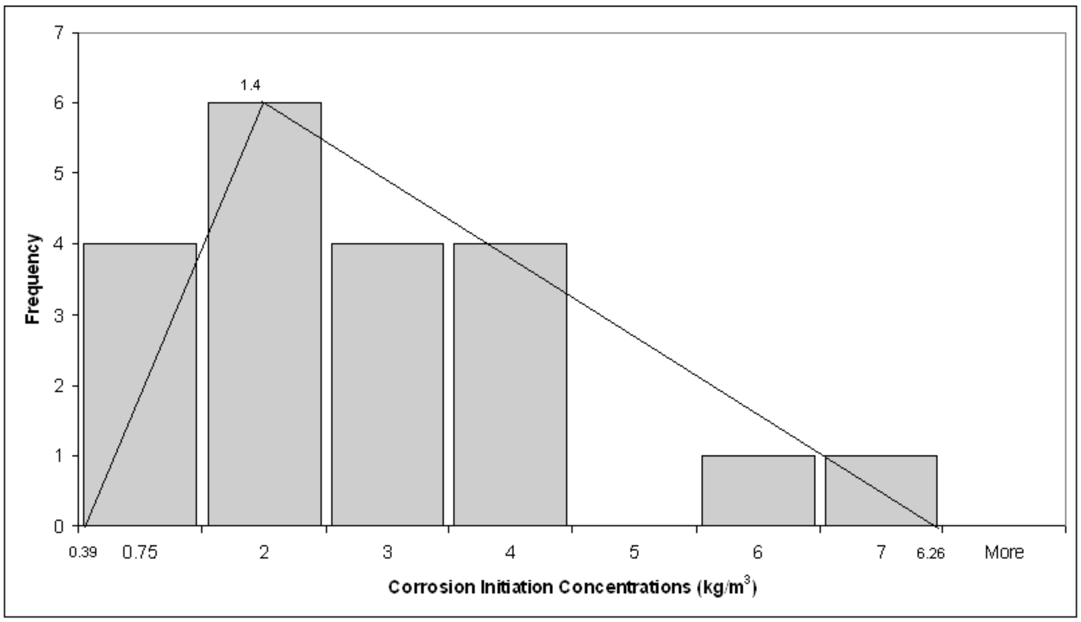

Figure 8. Corrosion Initiation Concentrations – Bare Steel

Twenty thousand values were generated in order to completely define the distribution. It was found that the actual number of values generated will not significantly affect the time to corrosion initiation estimations as long as a minimum of 2000 values are used. The generated distribution is presented in Figure 9.

Apparent Diffusion Coefficients (D_{ca})

The D_{ca} values that were determined from the sampled bridge deck cores were normalized to an age of 35 years using the methods described previously. These values were then used in the service life estimations. The actual values used are presented in the Results section.

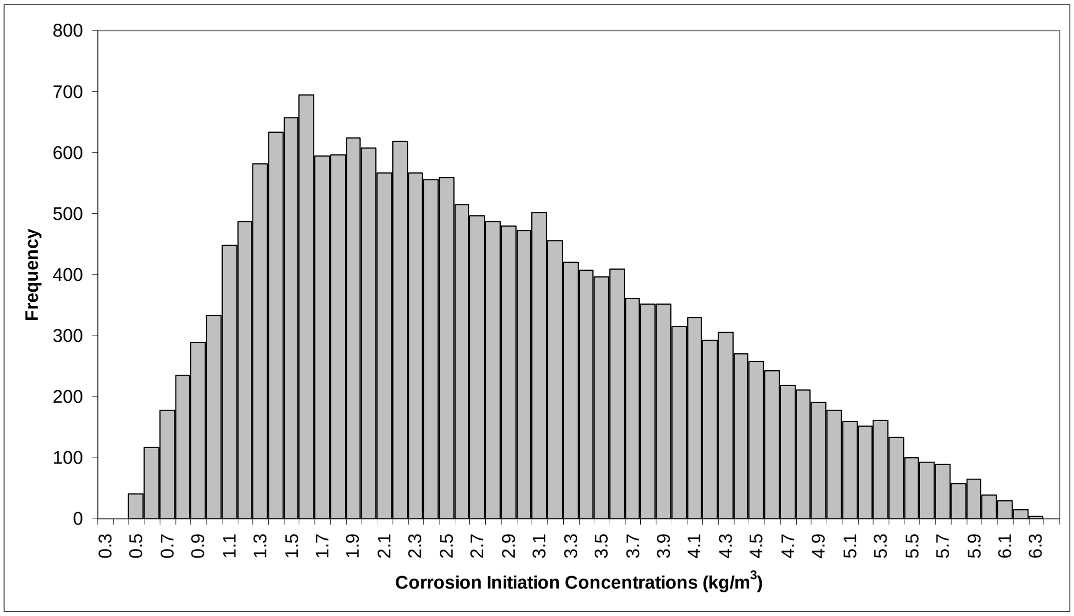

Figure 9. Corrosion Initiation Concentrations (Bare Steel - Randomly Generated)

Surface Chloride Concentrations (C_o)

The C_o values used in the service life model were the measured values taken from the deck cores at a depth of ½ in minus the estimated background chloride concentration. In instances where the chloride concentration reached a maximum at a depth greater than ½ in the higher concentration was used for C_o.

Cover Depths (x)

The cover depths determined from pachometer measurements were used as the input to the service life model. The pachometer measurements were validated by comparing the field measurements at the core locations to the actual cover depths that were measured in the laboratory for the 10 - 0.45 $^{w}/_{c}$ bridge decks. The field measurements differed from the actual values by as little as 1% to a maximum of 13%. The average difference was 5%, which is an insignificant amount when used in the service life model.

LIFE CYCLE COST ANALYSIS

The total cost of a bridge deck cannot be described by a one-time construction expenditure. There are always agency costs related to the operation, maintenance, repair and rehabilitation of a bridge deck throughout its' service life. Often times there are many alternatives available for maintaining a bridge deck, with different costs and timings associated with each. Due to the variety of bridge management options available it has become necessary to analyze the alternatives and select the most economical option. This, however, is not as simple as summing the expected costs for each alternative. The time-value of money and the affect on the user should also be considered. To assist in the comparison of alternatives an approach referred to as Life-Cycle Cost Analysis (LCCA) is commonly used. LCCA as related to bridges can be defined as “a set of economic principles and computational procedures for comparing initial and future costs to arrive at the most economical strategy for ensuring that a bridge will provide the services for which it was intended” (Hawk, 2003). LCCA may be separated into the five basic steps listed below:

1. Establish design alternatives
2. Determine activity timing
3. Estimate costs (agency and user)
4. Compute life-cycle costs
5. Analyze the results

LCCAs of Virginia Bridge Decks

LCCAs for bridge decks constructed under current design specifications are unnecessary because it is demonstrated in the results section of this repot that the estimated service life of 0.45 $^{w}/_{cm}$ bridge decks will exceed a specified design life of 100 years regardless of reinforcement type. Therefore, reinforcement type should be selected solely on a first-cost basis except in cases where extreme chloride exposure is expected.

However, the question remains as to what the best maintenance strategy is for bridge decks constructed under previous specifications. Therefore, multiple maintenance alternatives will be analyzed to determine the optimum maintenance strategy for these in-place bridge decks. The LCCAs will be conducted service life of 100 years and a base year of 2008. A base year of 2008 was selected because it is anticipated that 2008 will be the earliest possible time of implementation for this project. LCC comparisons will be based upon computed unit costs ($/SY). Using the calculated unit costs, LCCs for bridge decks of any size can be easily computed relative to their surface areas.

Establish Design Alternatives

Bridge deck LCCAs will be conducted for two possible repair/rehabilitation alternatives for preventing/repairing corrosion related deterioration. The initial condition of the bridge decks to be compared will be considered equivalent. Therefore, the only differences in the LCCA alternatives are related to the maintenance procedures. The two deck maintenance alternatives that will be investigated are polymer overlays and concrete overlays.

Maintenance Alternative 1: Polymer Overlays

Polymer overlays are used primarily to reduce the rate of ingress of water and chlorides into the concrete as well as to improve skid resistance, ride quality, and surface appearance (Krauss and Ferroni, 1986; Sprinkel, 1989). They are to be installed prior to extensive corrosion related deterioration. Polymer overlays are suitable for bridge decks that reflect between 0-1% corrosion related deterioration in the worst span lane. Bridge decks that have corrosion-deteriorated areas in excess of 1% should be repaired/rehabilitated using alternative maintenance strategies. Polymer overlays are not recommended for use on bridge decks that have any of the following characteristics (Weyers et al., 1993):

1. "Corrosion-induced delaminations and spalls
2. Cover concrete that is critically chloride-contaminated
3. Unsound concrete (tensile rupture strength less than 150 psi)
4. Poor drainage
5. Poor ride quality"

If the bridge deck being investigated reflects any of the above characteristics the use of a concrete overlay may be more appropriate.

The estimated service life of a polymer overlay ranges from 10 years for a bridge with a very high ADT (> 50,000) to 25 years for a bridge with a low to moderate ADT (< 5000) (Weyers et al., 1993). For purposes of this analysis polymer overlays will be investigated for service lives of 10, 15, and 25 years. In addition to the cost of the overlay the cost associated with 1% patching of the bridge deck at the time of the overlay will be taken into account. For an individual bridge deck it may be necessary to place multiple overlays in order to reach the desired service life. When that is the case the installation of the polymer overlay will become a recurring cost as well as the removal of preceding overlays.

Maintenance Alternative 2: Concrete Overlays

The second maintenance alternative that will be investigated is the use of concrete overlays as a deck rehabilitation measure. They are used as a repair/rehabilitation method for decks reflecting significant levels of corrosion related deterioration. The installation of concrete overlays requires that a specified depth of the cover concrete be removed by milling and the underlying concrete removed and patched as necessary.

Concrete overlays are typically used as a rehabilitation method for bridge decks that have reached their EFSL. As mentioned previously the EFSL for a bridge deck is defined in this project as the time at which 12% of the bridge deck has deteriorated in the worst span lane. Therefore, a maintenance strategy that specifies the use of a concrete overlay must consider the costs associated with 12% patching of the bridge deck prior to placement of the overlay. As demonstrated by this project the required patching will occur on average during the 16 years preceding the placement of the overlay, see Corrosion Propagation section.

The service life of a concrete overlay is estimated to be between 22 and 26 years and is dependent upon the severity of chloride exposure and condition of the underlying concrete, but is independent of ADT (Weyers et al., 1993). The overlay service life used in the following analyses is 25 years. The cost for 12% patching, milling, and grooving of the bridge deck for each required overlay is also included.

Determine Activity Timing

With the two maintenance alternatives identified the next step is to determine the timings of the associated maintenance activities. The activity timings presented in Table 2 represent those timings associated with a bridge deck that has a current deterioration level between 0 and 1%. Year zero does not represent the time at which the bridge deck is put in place but rather the time of analysis.

As shown, a bridge deck with 0 - 1% corrosion related damage would either require a polymer overlay in the current year or a concrete overlay approximately 15 years in the future. For the case of a polymer overlay, the 0 – 1% of deteriorated deck would be patched at the time of the overlay. Additionally, for subsequent polymer overlays there is a cost associated with the removal of the previous overlay. Concrete overlays are not placed until substantial deterioration is evident (12% of the worst span lane). The maintenance activity timings presented reflect the 12% of required patching prior to placement of the concrete overlay. For simplicity the patching has been estimated to occur in equal amounts of 6% at 5 and 10 years prior to the placement of the concrete overlay. The required milling and bridge deck grooving associated with a concrete overlay are also considered.

Table 2. LCCA Maintenance Activity Timing

Year	Polymer Overlays ADT			Concrete Overlays
	VH	H	M	
0	PO and 1% P	PO and 1% P	PO and 1% P	
5				6% P
10	OR, PO and 1% P			6% P
15		OR, PO and 1% P		M, CO and G
20	OR, PO and 1% P			
25			OR, PO and 1% P	
30	OR, PO and 1% P	OR, PO and 1% P		6% P
35				6% P
40	OR, PO and 1% P			M, CO and G
45		OR, PO and 1% P		
50	OR, PO and 1% P		OR, PO and 1% P	
55				6% P
60	OR, PO and 1% P	OR, PO and 1% P		6% P
65				M, CO and G
70	OR, PO and 1% P			
75		OR, PO and 1% P	OR, PO and 1% P	
80	OR, PO and 1% P			6% P
85				6% P
90	OR, PO and 1% P	OR, PO and 1% P		M, CO and G
95				
100				

It should be noted that the activity timings presented in Table 2 are only valid for bridge deck maintenance decisions made in the current year (2008). For bridge decks that do not currently require maintenance, activity-timing tables must be developed for future years. LCC comparison tables will be developed and presented for the maintenance alternatives where strategy decisions are to be made in the year 2008, 2018, 2028, 2038, 2048, and 2058.

It is important to note that the maintenance timings presented may be altered at the discretion of the engineer. The estimated service lives of the overlays are intended to reflect the average expected service life for a given set of circumstances. The actual service life of an overlay is dependent upon the severity of the environment to which it is exposed, the condition of the underlying deck, the quality of construction, and the level of traffic on the bridge. The purpose of the examples provided in this report is to present the concepts of LCCA rather than to make determinations for the maintenance strategies of individual bridge decks.

Estimate Costs

The next step in conducting the LCCA is to determine the costs associated with each maintenance alternative. As mentioned previously, the base year for comparison is 2008. Therefore, all maintenance expenditures presented in this section were adjusted to reflect their estimated costs in 2008. The costs were estimated using tabulated VDOT bid data from 1997, 1999, and 2004. The average inflation rate was determined for each bid item for the time period of 1997 – 2004. Using the 2004 cost data and the average inflation rate the costs were projected for the year 2008. The bid items associated with the two maintenance alternatives are presented below:

Alternative 1 – Polymer Overlays

- Patching – Type B – The removal and patching of deteriorated concrete to a depth below the first mat of reinforcement.
- Polymer Overlay – The placement of a multi-layer polymer overlay on the entire bridge deck.
- Polymer Overlay Removal – The removal of a previous polymer overlay prior to the placement of a subsequent overlay.
- Traffic Control – The cost associated with controlling the traffic over the lifetime of the project.
- User Costs – Costs incurred by the traveling public attributable to the construction project. Varies between projects and therefore will not be considered in the presented examples.

Alternative 2 – MSC/LMC Overlays

- Patching – Type B
- Milling Type A – The removal of the top ½ in of concrete prior to placement of a concrete overlay.
- Concrete Overlay – The placement of a concrete overlay with a specified depth of 1 ¼ in – 1 ¾ in
- Bridge Deck Grooving – The grooving of the concrete overlay after placement and curing.

- Traffic Control
- User Costs – Again, because user costs are site specific, they are not included in the presented examples. User costs include vehicle delay costs, vehicle operating costs, and accident costs. Procedures for calculating user costs are presented elsewhere. (FHWA, 2002)

The weighted average contract bid prices for the required construction items are presented in Table 3.

Table 3. Bid Data

VDOT Bid Data		
Bid Item	Contract Price*	
Bridge Deck Grooving (SY)	$5.14	1997
	$3.56	1999
	$3.98	2004
Deck Patch Type B (SY)	$145.70	1997
	$169.04	1999
	$314.82	2004
Milling Type A (SY)	$9.83	1997
	$8.62	1999
	$9.24	2004
Overlay – Latex or Silica (CY)	$839.03	1997
	$584.61	1999
	$1,085.83	2004
Overlay – Polymer (SY)	$19.19	1997
	$20.57	1999
	$23.40	2004
Remove Polymer Overlay (SY)	$15.25	1999

*Weighted Average

The weighted average contract price was calculated using Equation 3.

$$WA = \frac{\sum C_i \times Q_i}{Q_T} \qquad \text{Equation 3}$$

Where:

WA = Weighted average contract price
C_i = Contract price for an individual project
Q_i = Quantity of work for an individual project
Q_T = Total quantity of work for all projects

As shown in Table 3, several bid items reflect relatively steady inflation rates while others have substantial price fluctuations. The fluctuations may be due to variations in average project size, availability of materials, or bid competition. For those bid items that appear to have a continuous increase in cost over the 7-year period being investigated, the inflation rate will be determined and used to project prices for the year 2008. For bid items where significant price fluctuations are evident the average value will be used. The cost data used in the following analyses are presented in Table 4.

The cost data presented above are estimated average values and should not be used for the LCCA of an individual bridge deck. Construction costs vary widely due to the effects of bid quantity, bid competition, and geographic location.

Table 4. LCCA Cost Data

	Bridge Deck LCCA Cost Data ($/SY)		
Item	**Avg. Inflation Rate (%)**	**Average Cost ($)**	**2008 Projected Cost ($)**
Bridge Deck Grooving (SY)	----	$4.23	$4.23
Deck Patch Type B (SY)	11.6	----	$487.27
Milling Type A (SY)	----	$9.23	$9.23
Overlay – Latex or Silica (CY)/(SY)*			
Overlay – Polymer (SY)			
Remove Polymer Overlay (SY)			

* Cost calculated based upon an overlay depth of 2"

Bid Quantity Effects

For a given project, the mobilization, overhead, and profit costs are factored into a bid price. For projects with large quantities of work these costs are distributed over the entire project and will have little influence on the unit cost of a particular bid item. Thus, the engineer should take the quantity of required work into account when estimating costs for a particular project and make use of economies of scale.

Bid Competition Effects

The amount of transportation-related construction occurring within the state of Virginia at any given time is constantly changing. The same laws of supply and demand that govern the cost or value of any item also apply to the construction industry. At times when there is an oversupply of projects, contractors are not available to take on additional work and the average bid for a particular item will increase. Likewise, when there is a limited supply of projects and multiple contractors are competing for the same work the cost will be driven down. The effects that bid competition will have on an individual project are difficult to estimate, however, attempts by maintenance engineers to maintain steady work orders may help to negate these effects.

Geographic Location Effects

The effect that the location of a project has on cost can be substantial. Within Virginia, labor and material costs can vary significantly. The distance of the project from the necessary resources is also an important factor as the transportation costs for materials is often higher than the cost of the materials themselves. For most cases district engineers will be able to accurately estimate costs for their specific locality, but special cases may arise where the location of the project warrants additional consideration.

Traffic Control Costs

The traffic control (TC) costs related to a bridge deck maintenance project will vary by location, route type, ADT, and duration. Therefore, there is no single value that can be used for all LCCAs. In the following examples an average TC cost of $52.92/SY is used for concrete overlays. This value was determined in a previous study relating to bridge maintenance in Virginia (Pyc et al., 2000). To estimate the TC costs associated with a polymer overlay, the duration of the projects was considered. It is estimated that the application of a polymer overlay will take approximately 1/3 of the time that is required for a concrete overlay. Therefore, the reduction in TC costs should correspond with the reduction in construction time. Thus, TC costs for polymer overlays will be taken to be 1/3 of concrete overlays or $17.64/SY.

Compute Life-Cycle Costs

To compute the LCCs for this project a deterministic approach has been taken. A database of the distribution of times for specific maintenance events was not available. Therefore, a probabilistic approach is not possible.

As mentioned previously, the discount rate that is specified for use by government agencies is 5.1% for long-term projects (OMB, 2007). Therefore, a discount rate of 5.1% has been used in the following examples. However, it may be necessary to adjust the long-term discount rate to reflect the impacts of inflation.

Inflation Rates

It is common practice to use the consumer's price index (CPI) to compute the inflation of the general economy. However, the application of the inflation rate associated with the CPI to transportation related construction activities might not be valid because of the differences in the inflation of different products and services. To determine the appropriate rate of inflation for transportation construction activities three cost indexes were investigated: Engineering News Record (ENR) Construction Cost Index, FHWA Composite Construction Cost Index, and FHWA Structures Construction Cost Index. A comparison of the three construction-related indexes with the CPI is presented in Figure 10.

As shown all indexes follow the same general inflationary trend regardless of volatility within an individual index. Thus, it can be inferred that the indexes are not significantly different. Therefore, the real discount rates recommended for use by the Office of Management and Budget that are adjusted based upon the CPI may be used. Recall that the real discount rate is the discount rate adjusted for the effects of inflation.

As shown in Figure 10, the rate of inflation from 1983 to 2003 is relatively uniform and is slower than from 1973 to 1983, 8% versus 3%, respectively. Considering OMB's long-term interest rate of 5.1% and an inflation rate of 3%, the real discount rate would be approximately 2.1%. As of January 2007, the recommended real discount rate for projects exceeding 30-years in length is 3.0%, which is within reasonable agreement with the estimated real discount rate of 2.1% (OMB, 2007).

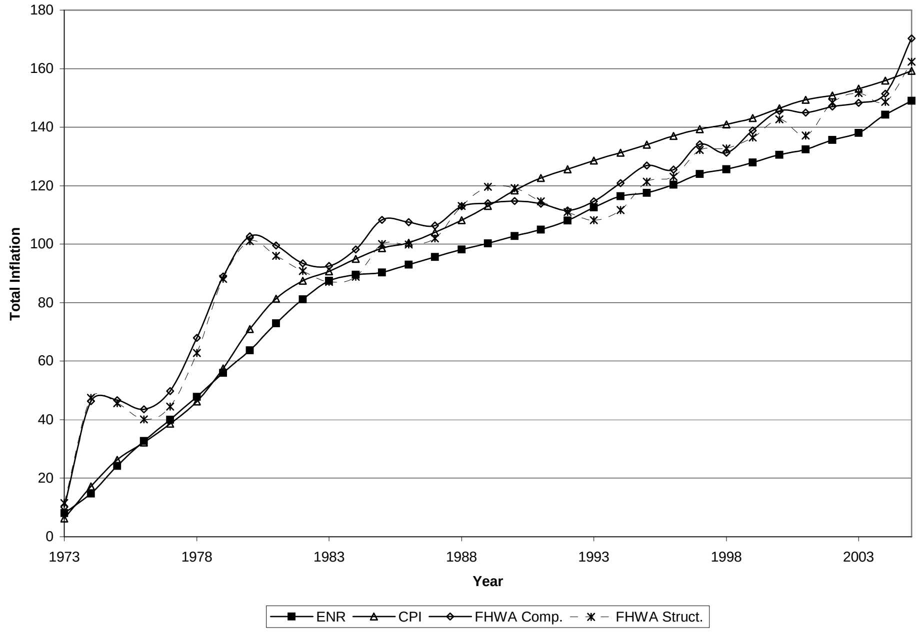

Figure 10. Index Comparison

RESULTS

Deck Surveys

The results of the deck damage surveys are presented in Tables 5-6. The damage levels presented are the total of both the measured visual damage and the damage determined through sounding for the right-hand traffic lane (critical traffic lane). The 0.47 $^{w}/_{c}$ bridge decks were resurveyed 3 years after the initial damage survey to provide data on corrosion propagation rates.

Table 5. 0.47 $^{w}/_{c}$ Bridge Deck Damage Surveys

0.47 w/c Bridge Decks				
Structure #	**Age at Survey**	**% Damaged 2003**	**Age at Survey**	**% Damaged 2006**
1-1804	34	3.3	37	5.3
1-6101	34	0.0	37	0.0
2-2007	33	0.8	36	2.3
3-1021	32	0.2	35	0.2
4-1062	34	0.0	37	0.0
4-2049	35	0.2	38	0.7
5-1800	33	1.8	36	3.3
6-1032	32	0.0	35	0.0
9-2801	33	1.7	36	3.0
9-6042	34	1.1	37	1.1

The 0.45 $^{w}/_{c}$ bridge decks reflected little to no damage due to their young age relative to the older 0.47 $^{w}/_{c}$ bridge decks.

Surface Chloride Concentrations

The C_o values determined from the chloride profiles of the bridge deck cores are presented in Table 7. The values represent the average chloride concentrations at a depth of ½ in below the surface of the deck. The results demonstrate the similarities between the three deck sets.

Table 6. 0.45 $^w/_c$ and 0.45 $^w/_{cm}$ Bridge Deck Damage Surveys

0.45 w/c Bridge Decks			0.45 w/cm Bridge Decks		
Structure #	**Age at Survey**	**% Damaged 2003**	**Structure #**	**Age at Survey**	**% Damaged 2003**
1-1132	15	0.0	1-1152	16	0.0
1-1133	15	0.0	1-2815	17	0.0
1-2820	17	0.0	1-2819	17	0.0
1-6051	13	0.0	2-1021	15	0.0
2-1020	17	0.0	3-1000	12	0.0
3-1003	15	0.0	5-2812	12	0.0
4-1007	13	0.0	8-1002	15	0.0
4-2901	12	0.0	8-1042	13	0.3
5-2547	19	0.0	9-1002	16	0.0
7-1920	12	0.3	9-6058	12	0.0
8-1019	19	0.0			
8-1133	16	0.0			
9-1014	15	0.0			
9-1031	13	0.1			
9-1098	15	0.0			
9-1139	16	0.0			

Table 7. Average Surface Chloride Concentrations

0.47 w/c Bridge Decks			0.45 w/c Bridge Decks			0.45 w/cm Bridge Decks		
Structure #	**Chloride Conc. kg/m^3**	**lbs/CY**	**Structure #**	**Chloride Conc. kg/m^3**	**lbs/CY**	**Structure #**	**Chloride Conc. kg/m^3**	**lbs/CY**
1-1804	6.52	11.05	1-1132	7.74	13.12	1-1152	6.54	11.08
1-6101	1.30	2.20	1-1133	6.45	10.93	1-2815	3.59	6.08
2-2007	3.85	6.53	1-2820	5.07	8.59	1-2819	6.94	11.76
3-1021	5.85	9.92	1-6051	2.42	4.10	2-1021	4.38	7.42
4-1062	1.74	2.95	2-1020	5.57	9.44	3-1000	1.91	3.24
4-2049	2.79	4.73	3-1003	2.86	4.85	5-2812	2.67	4.53
5-1800	0.62	1.05	4-1007	1.73	2.93	8-1002	2.74	4.64
6-1032	2.59	4.39	4-2901	1.72	2.92	8-1042	4.82	8.17
9-2801	2.80	4.75	5-2547	1.16	1.97	9-1002	2.66	4.51
9-6042	6.67	11.31	7-1920	3.33	5.64	9-6058	3.96	6.71
			8-1019	5.77	0.36			
			8-1133	3.59	0.22			
			9-1014	2.29	0.14			
			9-1031	2.83	0.18			
			9-1098	2.12	0.13			
			9-1139	2.83	0.18			

Cover Depths

The average of 40 – 114 cover depth measurements for the individual bridge decks are presented in Tables 8 - 10. The cover depth measurements were taken in the wheel paths of the critical deterioration area (right-hand traffic lane). As shown the average cover depths are generally higher for the 0.45 $^{w}/_{c}$ bridge deck sets. This is due to the VDOT specification change of an increase in cover depth that coincided with the decrease in the $^{w}/_{c}$ from 0.47 to 0.45.

Table 8. Average Cover Depths for 0.47 $^{w}/_{c}$ Bridge Decks

0.47 w/c Bridge Decks					
Structure #	Avg. Cover Depth mm	in	n	Standard Dev mm	in
1-1804	57.4	2.26	102	6.97	0.27
1-6101	53.2	2.09	92	7.32	0.29
2-2007	38.5	1.52	80	2.70	0.11
3-1021	52.1	2.05	48	6.63	0.26
4-1062	58.5	2.30	80	9.98	0.39
4-2049	52.5	2.07	60	6.91	0.27
5-1800	44.8	1.76	40	10.25	0.40
6-1032	62.2	2.45	80	7.81	0.31
9-2801	40.8	1.61	80	8.47	0.33
9-6042	60.7	2.39	42	6.18	0.24

Table 9. Average Cover Depths for 0.45 $^{w}/_{c}$ Bridge Decks

0.45 w/c Bridge Decks					
Structure #	Avg. Cover Depth mm	in	n	Standard Deviation mm	in
1-1132	55.4	2.18	84	6.95	0.27
1-1133	62.1	2.44	78	4.51	0.18
1-2820	72.7	2.86	80	5.73	0.23
1-6051	55.6	2.19	103	6.81	0.27
2-1020	55.4	2.18	114	6.50	0.26
3-1003	58.4	2.30	68	5.73	0.23
4-1007	61.1	2.41	68	3.74	0.15
4-2901	62.4	2.46	80	7.45	0.29
5-2547	65.0	2.56	80	6.03	0.24
7-1920	51.1	2.01	80	7.32	0.29
8-1019	63.5	2.50	102	5.83	0.23
8-1133	68.6	2.70	76	4.18	0.16
9-1014	50.1	1.97	40	3.63	0.14
9-1031	48.6	1.91	80	6.05	0.24
9-1098	56.7	2.23	80	5.53	0.22
9-1139	61.5	2.42	79	8.41	0.33

Diffusion Coefficients

Apparent diffusion coefficients were calculated for the sampled bridge decks using Fick's second law of diffusion. The D_{ca} values were then normalized to an age of 35 years using the methods described previously. The average calculated D_{ca} values and the average D_{ca} values projected at an age of 35 years are presented in Table 11(a – c). In general, there is little difference between normalized to age 35 years and the average calculated values for the age at sampling.

Table 10. Average Cover Depths for 0.45 $^{w}/_{cm}$ Bridge Decks

0.45 w/cm Bridge Decks					
Structure #	Avg. Cover Depth		n	Standard Deviation	
	mm	in		mm	in
1-1152	63.1	2.48	60	14.25	0.56
1-2815	63.9	2.52	103	5.50	0.22
1-2819	67.3	2.65	114	6.17	0.24
2-1021	61.8	2.43	48	4.15	0.16
3-1000	52.3	2.06	50	5.07	0.20
5-2812	63.8	2.51	40	4.12	0.16
8-1002	57.7	2.27	68	6.49	0.26
8-1042	58.7	2.31	56	11.12	0.44
9-1002	66.2	2.61	82	8.69	0.34
9-6058	55.9	2.20	40	4.34	0.17

Table 11a. Average Diffusion Coefficients

0.47 w/c Bridge Decks				
Structure #	Apparent D_c		D_{c35}	
	mm^2/yr	in^2/yr	mm^2/yr	in^2/yr
1-1804	35.74	0.055	36.35	0.056
1-6101	4.55	0.007	4.63	0.007
2-2007	6.3	0.010	6.35	0.010
3-1021	20.68	0.032	20.68	0.032
4-1062	3.63	0.006	3.69	0.006
4-2049	6.15	0.010	6.30	0.010
5-1800	7.97	0.012	8.04	0.012
6-1032	4.39	0.007	4.39	0.007
9-2801	4.72	0.007	4.76	0.007
9-6042	13.05	0.020	13.28	0.021

Table 11b. Average Diffusion Coefficients

0.45 w/cm Bridge Decks				
Structure #	Apparent D_c		D_{c35}	
	mm^2/yr	in^2/yr	mm^2/yr	in^2/yr
1-1152	2.3	0.004	1.52	0.002
1-2815	3.73	0.006	2.54	0.004
1-2819	5.35	0.008	3.63	0.006
2-1021	3.49	0.005	2.22	0.003
3-1000	1.96	0.003	1.12	0.002
5-2812	6.39	0.010	3.65	0.006
8-1002	5.09	0.008	3.25	0.005
8-1042	5.77	0.009	3.43	0.005
9-1002	11.82	0.018	7.79	0.012
9-6058	7.09	0.011	4.05	0.006

Table 11c. Average Diffusion Coefficients

0.45 w/c Bridge Decks				
Structure #	Apparent D_c		D_{c35}	
	mm^2/yr	in^2/yr	mm^2/yr	in^2/yr
1-1132	38.26	0.059	30.09	0.047
1-1133	82.64	0.128	64.98	0.101
1-2820	14.85	0.023	12.08	0.019
1-6051	51.72	0.080	39.19	0.061
2-1020	17.49	0.027	14.23	0.022
3-1003	46.02	0.071	36.19	0.056
4-1007	26.47	0.041	20.06	0.031
4-2901	26.18	0.041	19.43	0.030
5-2547	5.53	0.009	4.64	0.007
7-1920	56.44	0.087	41.88	0.065
8-1019	30.96	0.048	25.76	0.040
8-1133	24.06	0.037	19.26	0.030
9-1014	19.74	0.031	15.52	0.024
9-1031	36.82	0.057	27.90	0.043
9-1098	9.28	0.014	7.29	0.011
9-1139	40.98	0.064	32.80	0.051

Service Life Model Input Data

Histograms of the input data were developed for each of the three bridge deck sets to investigate the distributions of the input parameters. The histograms for the three bridge deck sets are presented in Figures 11 - 19.

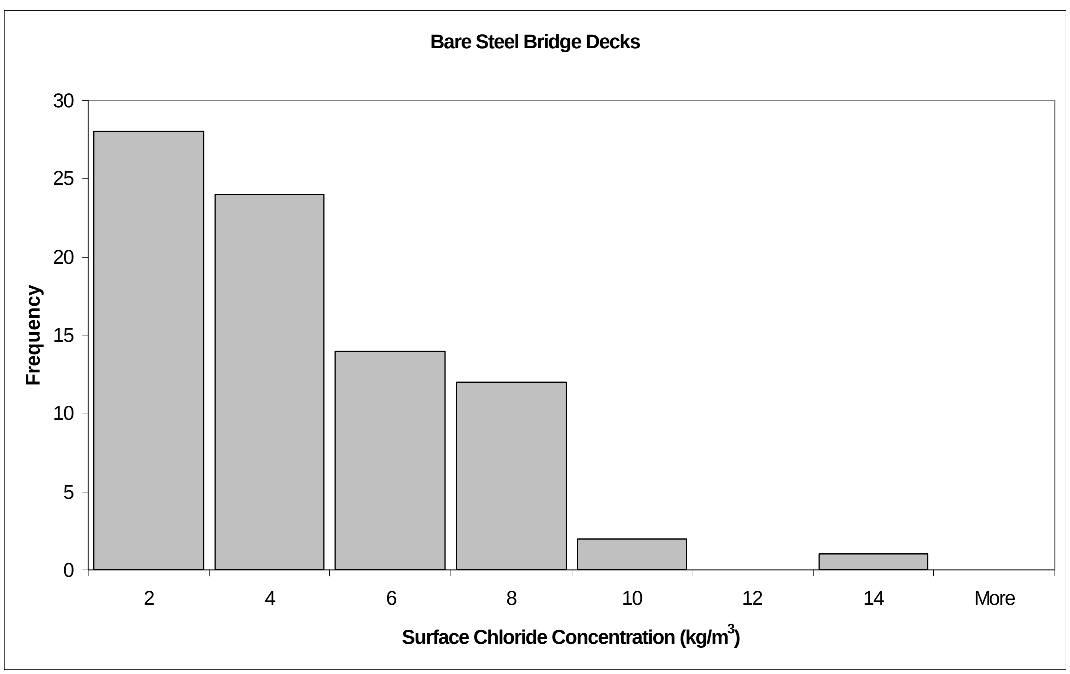

Figure 11. C_o Measurements – 0.47 $^w/_c$

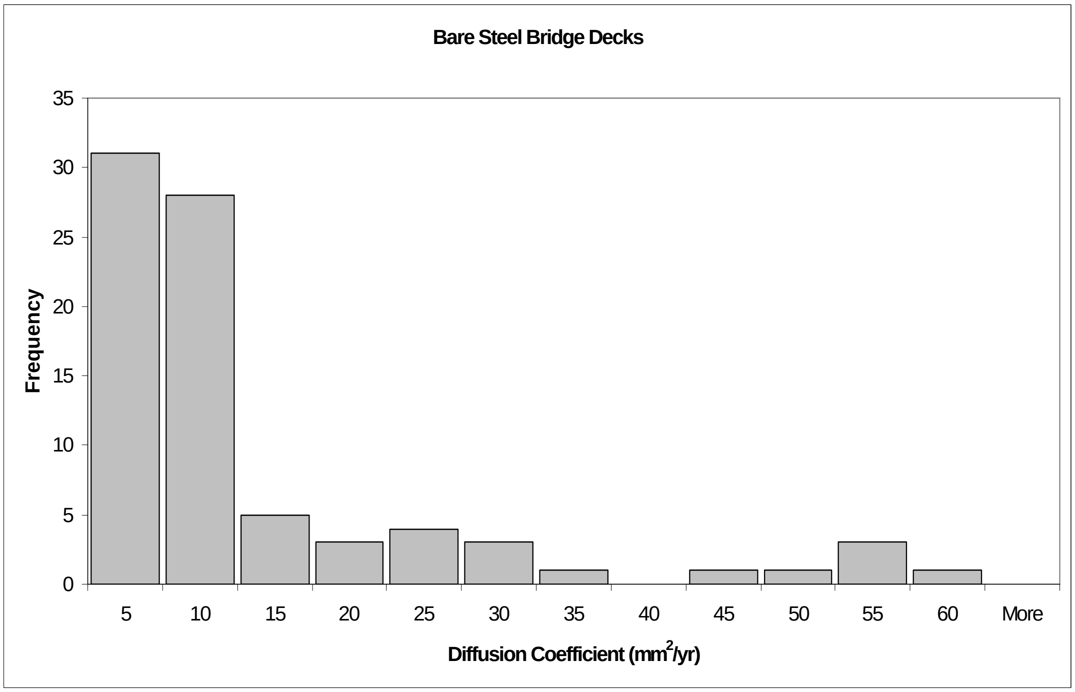

Figure 12. Diffusion Coefficients – 0.47 $^{w}/_{c}$

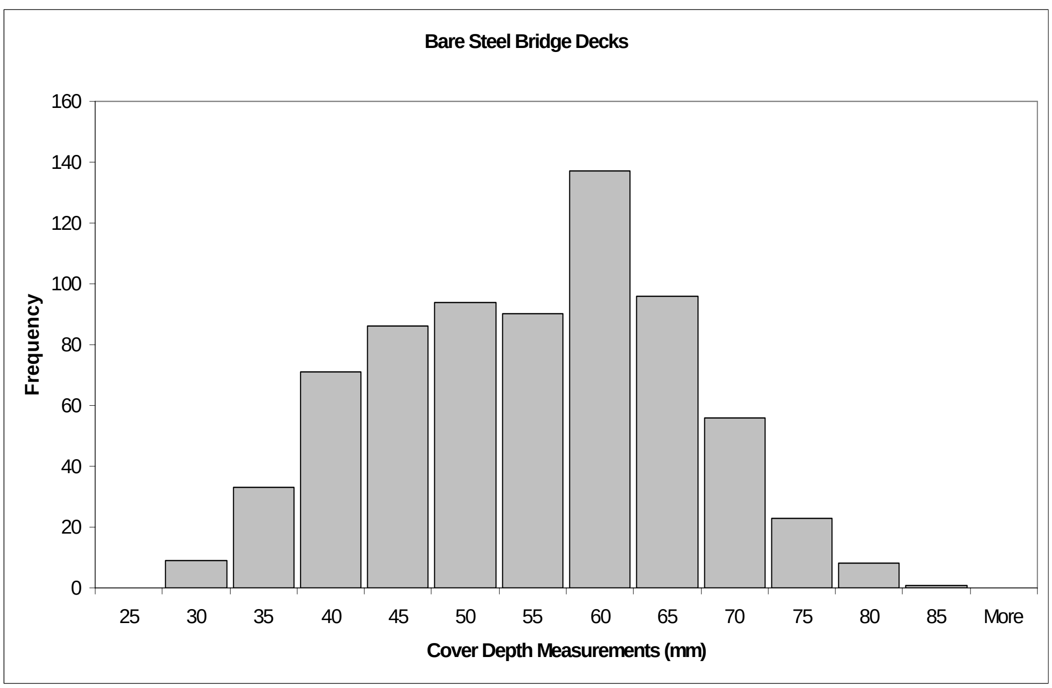

Figure 13. Cover Depth Measurements – 0.47 $^{w}/_{c}$

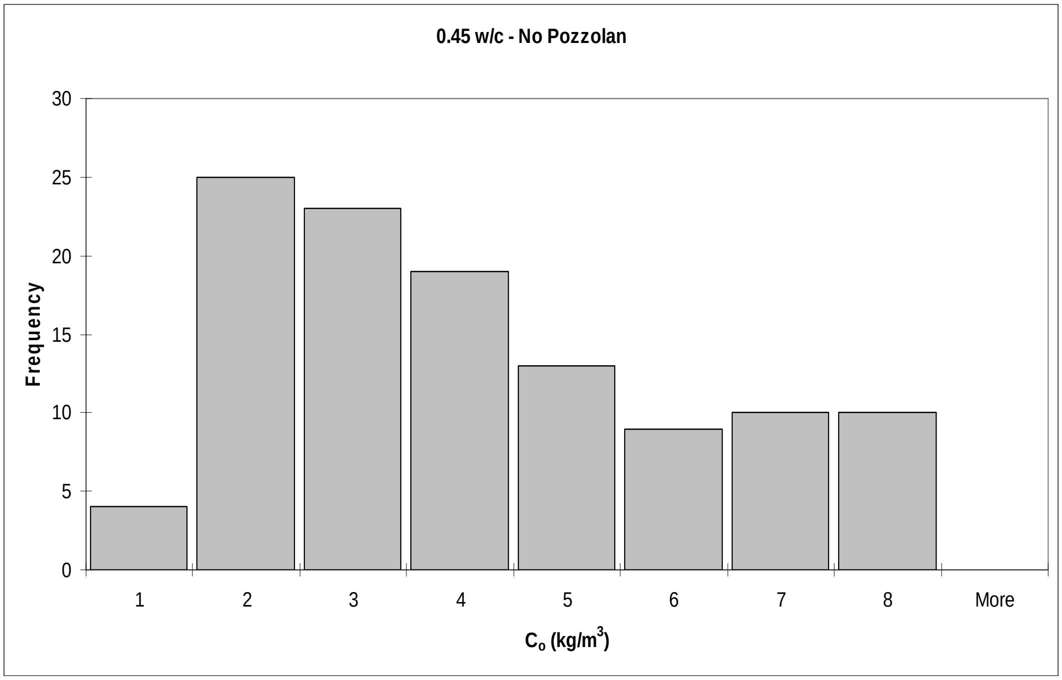

Figure 14. Surface Chloride Concentrations – 0.45 $^w/_c$

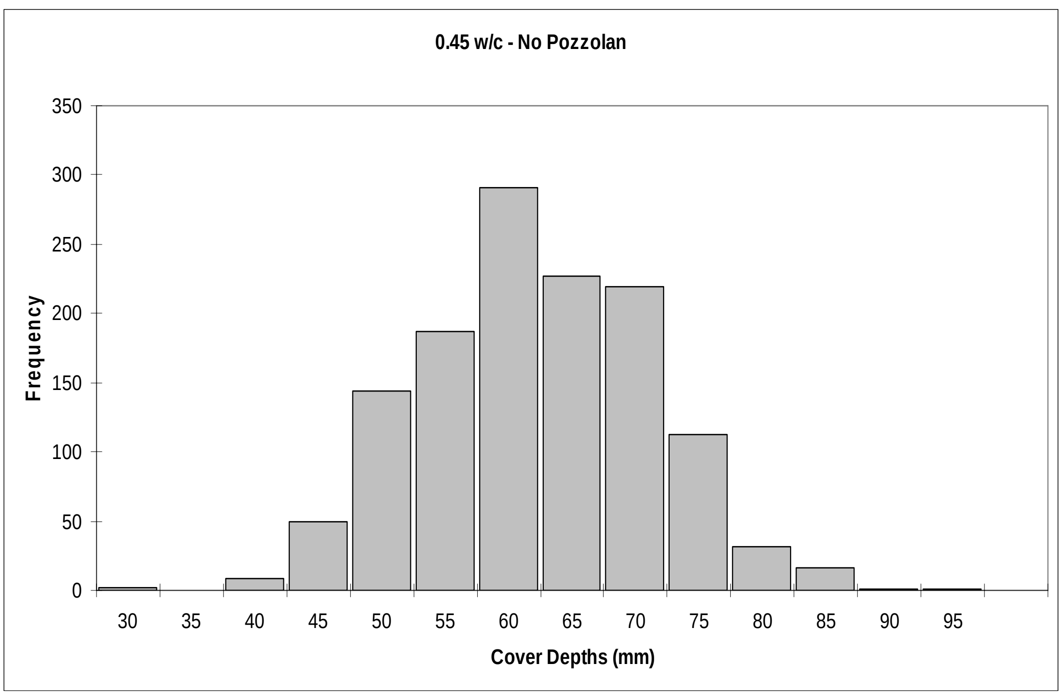

Figure 15. Cover Depth Measurements – 0.45 $^w/_c$

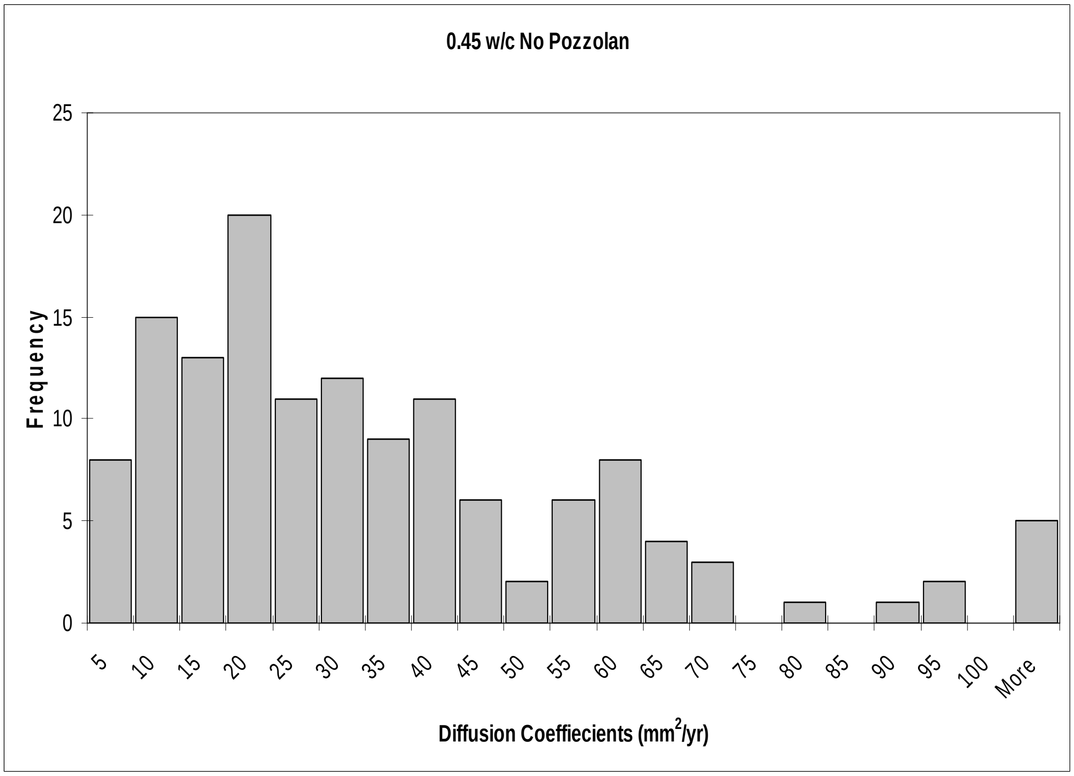

Figure 16. Diffusion Coefficients – 0.45 $^{w}/_{c}$

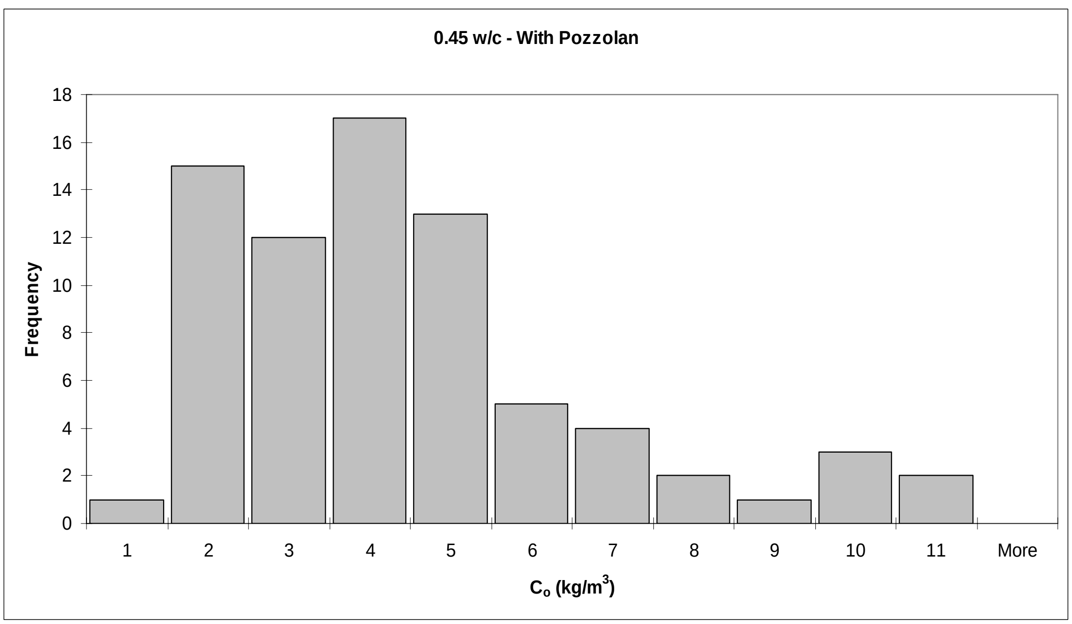

Figure 17. Surface Chloride Concentrations – 0.45 $^{w}/_{cm}$

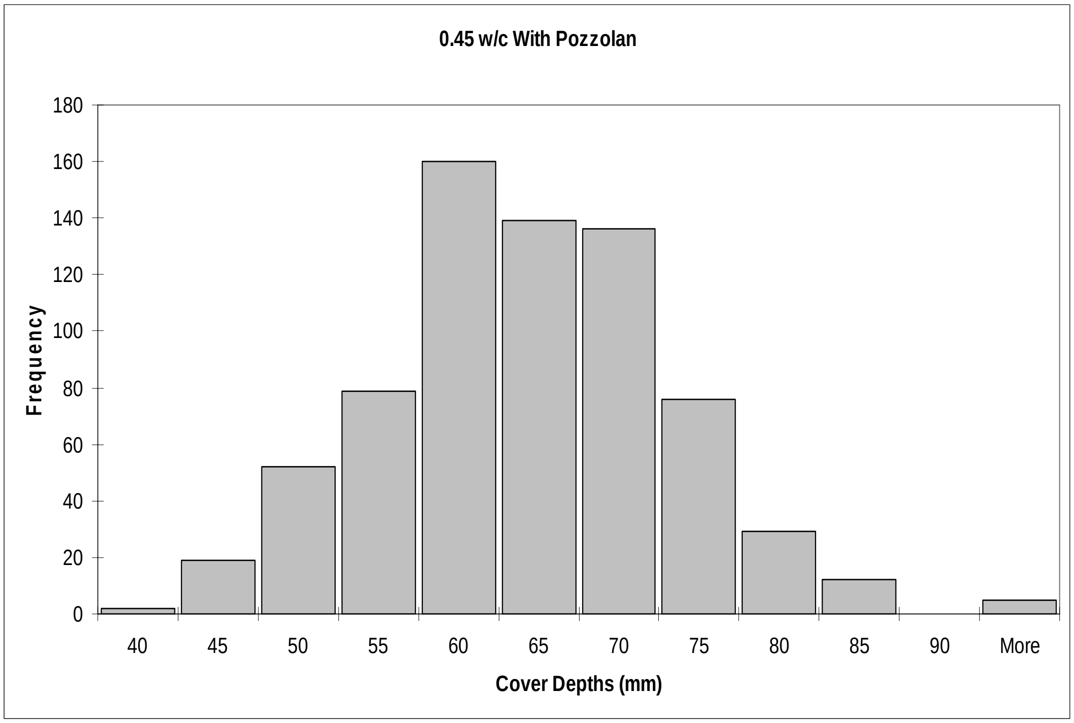

Figure 18. Cover Depth Measurements – 0.45 $^{w}/_{cm}$

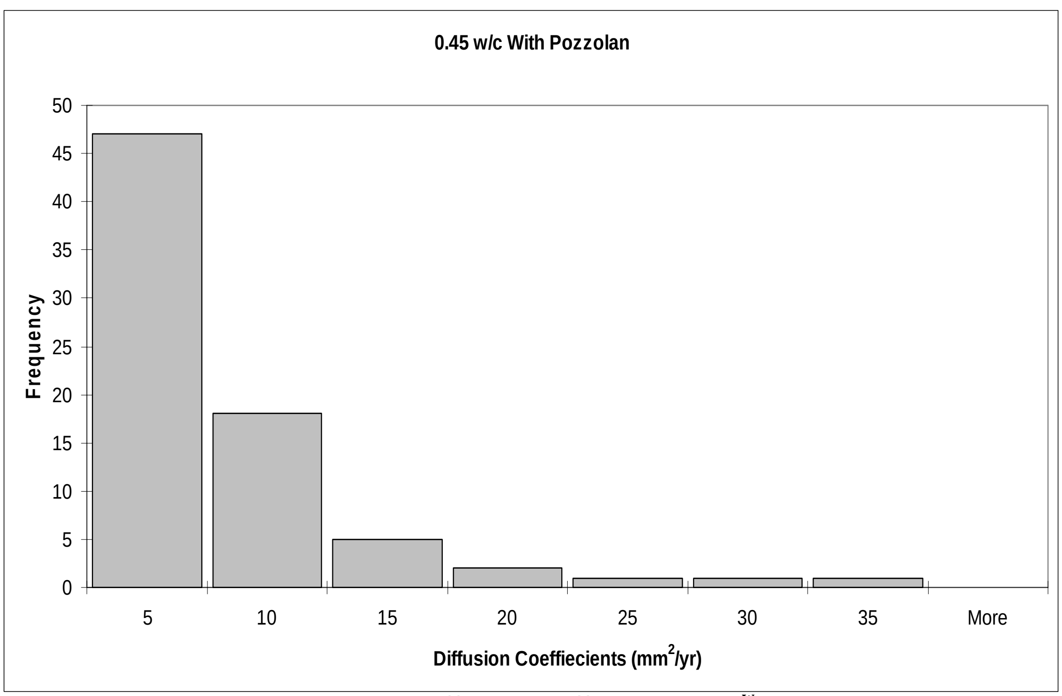

Figure 19. Diffusion Coefficients – 0.45 $^{w}/_{cm}$

The histograms presented above indicate that C_o, and D_c may be reasonably described by the gamma distribution while cover depths follow a normal distribution which is in agreement with previous studies (Pyc, 1998, Zemajtis, 1998, Kirkpatrick, 2001). For service life modeling purposes it may be possible to assign a distribution to the input parameters in cases where sufficient data are not available to permit the use of simple bootstrapping. For the case of modeling the bridge deck sets this is not necessary due to the large quantity of data available.

To estimating the service life of a bridge deck, corrosion threshold distribution for a given steel type, surface chloride concentrations, reinforcing cover depth, and the concrete chloride diffusion constants are needed. Thus, cover depth and surface chlorides need to be measured. Whereas, the chloride threshold values are provided in the model program and the measured chloride diffusion constants for the three types of concrete, w/c = 0.47, w/c = 0.45, and w/cm = 0.45, may be used for bridge decks within the Commonwealth of Virginia, see Appendix A.

Life Cycle Costs

LCC comparison tables were developed for bridges where a maintenance strategy may be selected within the next 50 years and are presented in 10-year intervals (Tables 12-23). The tables are presented with and without traffic control costs and user costs are not considered. Where bridge maintenance decisions are to be made in years other than those presented in Tables 11-32, the LCCs may be approximated by a linear interpolation between adjacent 10 year periods.

Table 12. LCC Comparison – 2008 – Without Traffic Control

2008 Without Traffic Control		Polymer Overlay ($/SY) Average Daily Traffic (ADT)			Concrete Overlay ($/SY)
	Year	**Very High**	**High**	**Moderate**	
Required Remaining Service Life	0	30.19	30.19	30.19	0.00
	5				20.25
	10	33.81			17.46
	15		29.17		53.73
	20	25.16			
	25			21.70	
	30	18.72	18.72		9.67
	35				8.34
	40	13.93			25.66
	45		12.02		
	50	10.37		10.37	
	55				4.62
	60	7.71	7.71		3.98
	65				12.26
	70	5.74			
	75		4.95	4.95	
	80	4.27			2.21
	85				1.90
	90	3.18	3.18		5.85
	95				
	100				

* ADT: Moderate = 5,000 to 25,000; High => 25,000; Very High => 50,000
* Real Discount Rate – 3.00%

Table 13. LCC Comparison – 2008 – With Traffic Control

2008 With Traffic Control		Polymer Overlay ($/SY) Average Daily Traffic (ADT)			Concrete Overlay ($/SY)
	Year	Very High	High	Moderate	
Required Remaining Service Life	0	47.83	47.83	47.83	0.00
	5				20.25
	10	46.94			17.46
	15		40.49		87.70
	20	34.93			
	25			30.13	
	30	25.99	25.99		9.67
	35				8.34
	40	19.34			41.88
	45		16.68		
	50	14.39		14.39	
	55				4.62
	60	10.71	10.71		3.98
	65				20.00
	70	7.97			
	75		6.87	6.87	
	80	5.93			2.21
	85				1.90
	90	4.41	4.41		9.55
	95				
	100				

* ADT: Moderate = 5,000 to 25,000; High => 25,000; Very High => 50,000
* Real Discount Rate – 3.00%

Table 14. LCC Comparison – 2018 – Without Traffic Control

2018 Without Traffic Control		Polymer Overlay ($/SY) Average Daily Traffic (ADT)			Concrete Overlay ($/SY)
	Year	Very High	High	Moderate	
Required Remaining Service Life	0	22.46	22.46	22.46	0.00
	5				15.06
	10	25.16			12.99
	15		21.70		39.98
	20	18.72			
	25			16.15	
	30	13.93	13.93		7.19
	35				6.21
	40	10.37			19.09
	45		8.94		
	50	7.71		7.71	
	55				3.44
	60	5.74	5.74		2.96
	65				9.12
	70	4.27			
	75		3.68	3.68	
	80	3.18			1.64
	85				1.42
	90	2.36	2.36		4.36
	95				
	100				

* ADT: Moderate = 5,000 to 25,000; High => 25,000; Very High => 50,000
* Real Discount Rate – 3.00%

Table 15. LCC Comparison – 2018 – With Traffic Control

2018 With Traffic Control		Polymer Overlay ($/SY)			Concrete Overlay ($/SY)
		Average Daily Traffic (ADT)			
Required Remaining Service Life	Year	Very High	High	Moderate	
	0	35.59	35.59	35.59	0.00
	5				15.06
	10	34.93			12.99
	15		30.13		65.26
	20	25.99			
	25			22.42	
	30	19.34	19.34		7.19
	35				6.21
	40	14.39			31.27
	45		12.41		
	50	10.71		10.71	
	55				3.44
	60	7.97	7.97		2.96
	65				14.89
	70	5.93			
	75		5.11	5.11	
	80	4.41			1.64
	85				1.42
	90	3.28	3.28		7.11
	95				
	100				

* ADT: Moderate = 5,000 to 25,000; High => 25,000; Very High => 50,000
* Real Discount Rate – 3.00%

Table 16. LCC Comparison – 2028 – Without Traffic Control

2028 Without Traffic Control		Polymer Overlay ($/SY)			Concrete Overlay ($/SY)
		Average Daily Traffic (ADT)			
Required Remaining Service Life	Year	Very High	High	Moderate	
	0	16.72	16.72	16.72	0.00
	5				11.21
	10	18.72			9.67
	15		16.15		29.75
	20	13.93			
	25			12.02	
	30	10.37	10.37		5.35
	35				4.62
	40	7.71			14.21
	45		6.65		
	50	5.74		5.74	
	55				2.56
	60	4.27	4.27		2.21
	65				6.79
	70	3.18			
	75		2.74	2.74	
	80	2.36			1.22
	85				1.05
	90	1.76	1.76		3.24
	95				
	100				

* ADT: Moderate = 5,000 to 25,000; High => 25,000; Very High => 50,000
* Real Discount Rate – 3.00%

Table 17. LCC Comparison – 2028 – With Traffic Control

2028 With Traffic Control		Polymer Overlay ($/SY)			Concrete Overlay ($/SY)
		Average Daily Traffic (ADT)			
	Year	Very High	High	Moderate	
Required Remaining Service Life	0	26.48	26.48	26.48	0.00
	5				11.21
	10	25.99			9.67
	15		22.42		48.56
	20	19.34			
	25			16.68	
	30	14.39	14.39		5.35
	35				4.62
	40	10.71			23.19
	45		9.24		
	50	7.97		7.97	
	55				2.56
	60	5.93	5.93		2.21
	65				11.08
	70	4.41			
	75		3.81	3.81	
	80	3.28			1.22
	85				1.05
	90	2.44	2.44		5.29
	95				
	100				

* ADT: Moderate = 5,000 to 25,000; High => 25,000; Very High => 50,000
* Real Discount Rate – 3.00%

Table 18. LCC Comparison – 2038 – Without Traffic Control

2038 Without Traffic Control		Polymer Overlay ($/SY)			Concrete Overlay ($/SY)
		Average Daily Traffic (ADT)			
	Year	Very High	High	Moderate	
Required Remaining Service Life	0	12.44	12.44	12.44	0.00
	5				8.34
	10	13.93			7.19
	15		12.02		22.14
	20	10.37			
	25			8.94	
	30	7.71	7.71		3.93
	35				3.44
	40	5.74			10.57
	45		4.95		
	50	4.27		4.27	
	55				1.90
	60	3.18	3.18		1.64
	65				5.05
	70	2.36			
	75		2.04	2.04	
	80	1.76			0.91
	85				0.78
	90	1.31	1.31		2.41
	95				
	100				

* ADT: Moderate = 5,000 to 25,000; High => 25,000; Very High => 50,000
* Real Discount Rate – 3.00%

Table 19. LCC Comparison – 2038 – With Traffic Control

2038 With Traffic Control		Polymer Overlay ($/SY)			Concrete Overlay ($/SY)
		Average Daily Traffic (ADT)			
	Year	Very High	High	Moderate	
Required Remaining Service Life	0	19.71	19.71	19.71	0.00
	5				8.34
	10	19.34			7.19
	15		16.68		36.13
	20	14.39			
	25			12.41	
	30	10.71	10.71		3.98
	35				3.44
	40	7.97			17.26
	45		6.87		
	50	5.93		5.93	
	55				1.90
	60	4.41	4.41		1.64
	65				8.24
	70	3.28			
	75		2.83	2.83	
	80	2.44			0.91
	85				0.78
	90	1.82	1.82		3.94
	95				
	100				

* ADT: Moderate = 5,000 to 25,000; High => 25,000; Very High => 50,000
* Real Discount Rate – 3.00%

Table 20. LCC Comparison – 2048 – Without Traffic Control

2048 Without Traffic Control		Polymer Overlay ($/SY)			Concrete Overlay ($/SY)
		Average Daily Traffic (ADT)			
	Year	Very High	High	Moderate	
Required Remaining Service Life	0	9.25	9.25	9.25	0.00
	5				6.21
	10	10.37			5.35
	15		8.94		16.47
	20	7.71			
	25			6.65	
	30	5.74	5.74		2.96
	35				2.56
	40	4.27			7.87
	45		3.68		
	50	3.18		3.18	
	55				1.42
	60	2.36	2.36		1.22
	65				3.76
	70	1.76			
	75		1.52	1.52	
	80	1.31			0.68
	85				0.58
	90	0.97	0.97		1.79
	95				
	100				

* ADT: Moderate = 5,000 to 25,000; High => 25,000; Very High => 50,000
* Real Discount Rate – 3.00%

Table 21. LCC Comparison – 2048 – With Traffic Control

2048 With Traffic Control		Polymer Overlay ($/SY)			Concrete Overlay ($/SY)
		Average Daily Traffic (ADT)			
Required Remaining Service Life	Year	Very High	High	Moderate	
	0	14.66	14.66	14.66	0.00
	5				6.21
	10	14.39			5.35
	15		12.41		26.88
	20	10.71			
	25			9.24	
	30	7.97	7.97		2.96
	35				2.56
	40	5.93			12.84
	45		5.11		
	50	4.41		4.41	
	55				1.42
	60	3.28	3.28		1.22
	65				6.13
	70	2.44			
	75		2.11	2.11	
	80	1.82			0.68
	85				0.58
	90	1.35	1.35		2.93
	95				
	100				

* ADT: Moderate = 5,000 to 25,000; High => 25,000; Very High => 50,000
* Real Discount Rate – 3.00%

Table 22. LCC Comparison – 2058 – Without Traffic Control

2058 Without Traffic Control		Polymer Overlay ($/SY)			Concrete Overlay ($/SY)
		Average Daily Traffic (ADT)			
Required Remaining Service Life	Year	Very High	High	Moderate	
	0	6.89	6.89	6.89	0.00
	5				4.62
	10	7.71			3.98
	15		6.65		12.26
	20	5.74			
	25			4.95	
	30	4.27	4.27		2.21
	35				1.90
	40	3.18			5.85
	45		2.74		
	50	2.36		2.36	
	55				1.05
	60	1.76	1.76		0.91
	65				2.80
	70	1.31			
	75		1.13	1.13	
	80	0.97			0.50
	85				0.43
	90	0.72	0.72		1.34
	95				
	100				

* ADT: Moderate = 5,000 to 25,000; High => 25,000; Very High => 50,000
* Real Discount Rate – 3.00%

Table 23. LCC Comparison – 2058 – With Traffic Control

2058 With Traffic Control		Polymer Overlay ($/SY)			Concrete Overlay ($/SY)
		Average Daily Traffic (ADT)			
Required Remaining Service Life	Year	Very High	High	Moderate	
	0	14.66	14.66	14.66	0.00
	5				4.62
	10	10.71			3.98
	15		9.24		20.00
	20	7.97			
	25			6.87	
	30	5.93	5.93		2.21
	35				1.90
	40	4.41			9.55
	45		3.81		
	50	3.28		3.28	
	55				1.05
	60	2.44	2.44		0.91
	65				4.56
	70	1.82			
	75		1.57	1.57	
	80	1.35			0.50
	85				0.43
	90	1.01	1.01		2.18
	95				
	100				

* ADT: Moderate = 5,000 to 25,000; High => 25,000; Very High => 50,000
* Real Discount Rate – 3.00%

DISCUSSION

Validation of Service Life Model

The service life model that will be used for this project was indirectly validated by comparing the predicted service lives for a set of 129 bridge decks in Virginia to their actual recorded service lives. (Kirkpatrick, 2001) To further extend the validation and assess the accuracy of the model, the predicted service lives for the 0.47 $^{w}/_{c}$ bridge decks were compared to actual measured deterioration levels. The 0.47 $^{w}/_{c}$ bridge decks were investigated because they are the oldest and reflect the most damage. The younger 0.45 $^{w}/_{c}$ bridge decks have insufficient damage to correlate the service life model to actual field conditions. Ten estimations of the time to corrosion initiation were conducted using the actual field determined input data presented in the results section and the average time is presented in Table 24. The individual data measurements were used in the corrosion initiation estimations as opposed to the average values in order to incorporate the effects of input data variability.

Table 24. Average Time to Corrosion Initiation (0.47 $^{w}/_{c}$ Bare Steel Bridge Decks)

% Corroded	Avg. Time to Corrosion Initiation (years)	Standard Deviation (years)	C.V. (%)
2	30.7	1.5	5.0

As shown the standard deviation is 1.5 years with a C.V. of 5.0 %. This level of variability was been deemed acceptable for this application.

As determined previously using the Liu/Weyers and Vu, Stewart, and Mullard corrosion propagation models the time to excessive concrete cracking is estimated to be 6 years for bare steel bridge decks. Thus, the total time period for the 0.47 $^{w}/_{c}$ set to reach a deterioration level of 2% is 37 years.

From the damage surveys that were conducted on the 0.47 $^{w}/_{c}$ bridge decks, approximately 2% of the total area of the bridge deck set is currently showing signs of corrosion damage (spalling, patches, or delaminations). The average age of the decks is 36.4 years with a range of 3 years and the predicted age of the set is 37 years. Thus, for this set of bridge decks the service life model considered to be an acceptable accurate predictor of service life for at least low levels of damage.

Comparison of Key Parameters

The key service life parameters (D_c, C_o, and x) from the three bridge deck sets were investigated to determine if there were significant differences between the sets. Single factor Analysis of Variance (ANOVA) comparisons were conducted for each combination of sets at the 95% confidence limit. The average values for the key parameters are presented in Table 25.

Table 25. Key Parameter Summary

Parameter	0.45 w/c	0.45 w/cm	0.47 w/c
Diffusion Coefficient (mm^2/yr)/(in^2/yr)	26.3/0.04	3.45/0.005	10.93/0.02
Surface Chloride Concentration (kg/m^3)/(pcf)	3.47/0.22	3.95/0.25	3.53/0.22
Cover Depths (mm)/(in)	59.4/2.34	61.5/2.42	52.2/2.06

Differences in D_{ca} at a projected age of 35 years were investigated first. It was determined that there are significant differences between all sets. The ANOVA's for the D_{ca} comparisons are presented in Tables 26-29. The differences between projected D_{ca} values indicate that the quality of the concrete varies significantly between sets. This was expected due to the changes in construction specifications.

Table 26. D_{ca} Comparison – 0.45 w/c to 0.45 w/cm.

SUMMARY						
Groups	**Count**	**Sum**	**Average**	**Variance**		
0.45 w/c	137	3603.2	26.3	567.4		
0.45 w/cm	75	258.6	3.4	12.2		
ANOVA						
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**Fcrit**
Between Groups	25311.2	1	25311.2	68.1	1.7E-14	3.9
Within Groups	78065.1	210	371.7			
Total	103376.2	211				

Table 27. D_{ca} Comparison – 0.45 w/cm to 0.47 w/c

SUMMARY						
Groups	**Count**	**Sum**	**Average**	**Variance**		
0.45 w/cm	75	258.6	3.4	12.2		
0.47 w/c	81	885.3	10.9	180.1		
ANOVA						
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**Fcrit**
Between Groups	2179.8	1	2179.8	21.9	6.2E-06	3.9
Within Groups	15310.9	154	99.4			
Total	17490.7	155				

Table 28. D_{ca} Comparison – 0.47 w/c to 0.45 w/c

SUMMARY						
Groups	**Count**	**Sum**	**Average**	**Variance**		
0.47 w/c	81	885.3	10.9	180.1		
0.45 w/c	137	3603.2	26.3	567.4		
ANOVA						
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**Fcrit**
Between Groups	12026.6	1	12026.6	28.4	2.51E-7	3.9
Within Groups	91575.6	216	424.0			
Total	103602.3	217				

The ANOVA's presented above can be interpreted by comparing the calculated F value to the F_{crit} value as well as by comparing the p-value to the 95% confidence level. The groups being compared are said to be statistically different if the calculated F value is greater than the F_{crit} value. The greater the difference between the two values, the greater the statistical difference. Additionally, if the calculated p-value is less than 1 minus the confidence limit, 1-0.95 = 0.05 for this case, the groups being compared are said to be statistically different. The lower the p-value, the greater the confidence in the decision will be. As presented above, the confidence in the statistical difference between the calculated D_{ca} values of the three data sets is high due to the large differences between F and F_{crit}. The calculated p-values are also well below the 0.05 value associated with a confidence limit of 95%. Thus, the diffusion coefficient for the w/cm = 0.45 is significantly lower than the w/c = 0.45 and 0.47. Whereas, the w/c = 0.47 diffusion constant is significantly less than the w/c = 0.45 diffusion constant which was a completely unexpected result.

The second parameter to be investigated was C_o. It was determined that the differences between the average surface chloride concentrations are not significant with the calculated F values being lower than F_{crit} and the p-values being greater than 0.05 in all cases. Thus, indicating that C_o is not related to length of exposure (beyond 10-15 years of age) or concrete type for the study groups, but is a function of the chloride exposure conditions. This confirms that all three sets have similar chloride exposure conditions. The ANOVA's for C_o are presented in Table 29-31.

Table 29. C_o Comparison – 0.45 w/c to 0.45 w/cm.

SUMMARY						
Groups	**Count**	**Sum**	**Average**	**Variance**		
0.45 w/c	137	476.0	3.5	3.7		
0.45 w/cm	75	296.1	3.9	5.4		
ANOVA						
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**Fcrit**
Between Groups	10.9	1	10.9	2.5	0.11	3.9
Within Groups	895.5	210	4.3			
Total	906.4	211				

Table 30. C_o Comparison – 0.45 w/cm to 0.47 w/c

SUMMARY						
Groups	**Count**	**Sum**	**Average**	**Variance**		
0.45 w/cm	75	296.1	3.9	5.4		
0.47 w/c	81	285.9	3.5	6.1		
ANOVA						
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**Fcrit**
Between Groups	6.8	1	6.8	1.2	0.3	3.9
Within Groups	884.5	154	5.7			
Total	891.3	155				

Table 31. C_o Comparison – 0.47 w/c to 0.45 w/c

SUMMARY						
Groups	**Count**	**Sum**	**Average**	**Variance**		
0.47 w/c	81	285.9	3.5	6.1		
0.45 w/c	137	476.0	3.5	3.7		
ANOVA						
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**Fcrit**
Between Groups	0.2	1	0.2	0.0	0.9	3.9
Within Groups	985.4	216	4.6			
Total	985.6	217				

The last input parameter to be investigated was cover depth. The cover depth comparison ANOVA's are presented in Tables 32-34. It was determined that there were significant differences between all three bridge deck sets. The F values were much greater than the F_{crit} values for comparisons between .45 $^{w}/_{c}$ bridge decks and .47 $^{w}/_{c}$ bridge decks. This was expected because the 0.45 $^{w}/_{c}$ bridge decks were constructed under specifications that required larger cover depths than the 0.47 $^{w}/_{c}$ bridge decks. The cover depth requirement was increased at the same time that the $^{w}/_{c}$ specifications were decreased. However, it is interesting that there is a significant difference between those decks containing supplemental cementing materials and those that do not although the average difference is to be considered small, 0.08 in (2.1 mm). Whereas, the other differences are considerably larger, 9 mm and 7.2 mm for $^{w}/_{c}$ of 0.47 and $^{w}/_{c\ m}$ of 0.45 and $^{w}/_{c}$ = 0.47 and $^{w}/_{c}$ = 0.45, respectively.

Table 32. Cover Depth Comparison – 0.47 w/c to 0.45 w/cm

SUMMARY						
Groups	**Count**	**Sum**	**Average**	**Variance**		
0.47 w/c	704	36732.7	52.2	119.2		
0.45 w/cm	709	43633.9	61.5	79.0		
ANOVA						
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**Fcrit**
Between Groups	30985.5	1	30985.5	312.9	2.14E-63	3.8
Within Groups	139733.5	1411	99.0			
Total	170719.0	1412				

Table 33. Cover Depth Comparison – 0.45 w/cm to 0.45 w/c

SUMMARY						
Groups	**Count**	**Sum**	**Average**	**Variance**		
0.45 w/cm	709	43633.9	61.5	79.0		
0.45 w/c	1291	76688.4	59.4	76.4		
ANOVA						
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**Fcrit**
Between Groups	2096.9	1	2096.9	27.1	2.11E-07	3.8
Within Groups	154489.9	1998	77.3			
Total	156586.8	1999				

Table 34. Cover Depth Comparison – 0.45 w/c to 0.47 w/c

SUMMARY						
Groups	**Count**	**Sum**	**Average**	**Variance**		
0.45 w/c	1291	76688.4	59.4	76.4		
0.47 w/c	704	36732.7	52.2	119.2		
ANOVA						
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**Fcrit**
Between Groups	23782.4	1	23782.4	259.9	4.63E-55	3.85
Within Groups	182352.7	1993	91.5			
Total	206135.1	1994				

Global Analysis

As stated previously the primary objective of this project is to model the service life of the investigated bridge decks as three distinct sets: 0.47 $^{w}/_{c}$, 0.45 $^{w}/_{c}$, and 0.45 $^{w}/_{cm}$. The analyses were conducted to investigate the influence of the specification changes relating to increased cover depths, lowered $^{w}/_{c}$ ratios, and the addition of supplemental cement materials. Although a statistical analysis of the C_o values indicated that there was no significant difference between sets, the C_o values from the 0.47 $^{w}/_{c}$ bridge deck set were used during the analysis of all three sets to remove any variability related chloride exposure.

0.47 $^{w}/_{c}$ Bridge Decks

The 0.47 $^{w}/_{c}$ set was the first set to be analyzed. The input data that was used for the service life model included 84 C_o measurements, 704 cover depth measurements, and 84 D_{ca} values adjusted to an age of 35 years. The 22 years added to the time to 2% corrosion initiation is the result of 6 years to corrosion cracking of 2% of the bridge deck plus 16 years for the damage to propagate from 2% to 12%, the time at which an overlay is needed. The results of the service life model are presented in Table 35.

Table 35. Service Life Estimates – 0.47 $^{w}/_{c}$ Bridge Decks

	0.47 w/c		
	Time (years)	**Standard Deviation (years)**	**C.V. %**
Time to 2% Initiation	31	1.5	5.0
Estimated Service Life	53	----	----

0.45 $^{w}/_{c}$ and 0.45 $^{w}/_{(cm)}$ Bridge Decks

The same methodology was used to estimate the influence of the concrete quality used to construct the 0.45 $^{w}/_{c}$ bridge decks. By doing so, a direct comparison of concrete quality between sets is possible. The data used in the service life model for concrete with and without a supplemental cementing material were presented in Figures 15, 16, 18 and 19 previously. The total number of data points used was as follows: w/c; D_{ca} at 35 years – 114 values, Cover Depth – 1105 values; w/cm; D_{ca} at 35 years – 98 values, Cover Depth – 868 values.

The 84 surface chloride concentrations from the 0.47 $^{w}/_{c}$ bridge decks were used as the input for the 0.45 $^{w}/_{c}$ decks in order to remove any environmental influence from the analysis. Additionally, the D_{ca} values that were calculated for the 0.45 $^{w}/_{c}$ decks were adjusted to reflect the time-dependency of the diffusion values as described previously. The results of the service life model are presented in Table 36 for the 0.45 $^{w}/_{c}$ bridge decks.

Table 36. Service Life Estimates - 0.45 $^{w}/_{c}$ Bridge Decks

	0.45 w/c Time (years)	0.45 w/c Standard Deviation (years)	0.45 w/c C.V. %	0.45 w/cm Time (years)	0.45 w/cm Standard Deviation (years)	0.45 w/cm C.V. %
Time to 2% Initiation	21	0.4	1.9	169	4.8	2.8
Estimated Service Life	43	----	----	191	----	----

Comparison of 0.47 $^{w}/_{c}$ and 0.45 $^{w}/_{c}$ Bridge Decks

Analysis of the service life estimates at the 2% corrosion initiation level for the three bridge deck sets demonstrated that the 0.45 $^{w}/_{c}$ bridge decks with supplemental cementing materials were predicted to be the most durable. The results demonstrate the influence of larger cover depths and the lower D_{ca} values associated with the 0.45 $^{w}/_{cm}$ set of bridge decks. More importantly, however, is the lower predicted service life of the 0.45 $^{w}/_{c}$ bridge decks as compared to the 0.47 $^{w}/_{c}$ bridge decks, 21 years and 31 years, respectively. Although the predictions take into account the larger cover depths of the 0.45 $^{w}/_{c}$ decks, the larger D_{ca} values have negated the influence of the larger cover depths. The higher D_{ca} values for the w/c 0.45 decks may be due to quality control/construction issues with the newer 0.45 $^{w}/_{c}$ decks. Also, it should be noted that the 10 - 0.47 $^{w}/_{c}$ bridge decks used in this study were selected from a previous study sample of which only 68% survived. (Kirkpatrick, 2001) The bridges that had already been rehabilitated were removed from the data set, as an accurate chloride analysis and damage survey would be impossible. Therefore, the 10 decks selected were from the better performing 68%, which may place some bias on the sample set.

The corrosion initiation period for 2% damage estimates illustrates that the addition of supplemental cementing materials improves the long-term durability of bridge decks by decreasing the concrete diffusivity. It appears that reducing the $^{w}/_{c}$ of the concrete had a negligible effect. It may be inferred that the study sample of the older 0.47 $^{w}/_{c}$ concrete is of a higher quality than the newer 0.45 $^{w}/_{c}$ study sample.

Alternative Reinforcements

As discussed previously, alternative reinforcements can potentially increase the service life of bridge decks substantially. In order to analyze the various alternatives, D_c, C_o, and cover depth values from the concrete containing supplemental cementing materials were used as input to the service life model. These values were selected for use because they best represent the current state of bridge deck construction in Virginia.

Galvanized Steel

The chloride threshold values for galvanized steel are estimated to be 2.5 times greater than carbon steel (Yeomans, 2004). Corrosion initiation values were generated by simply multiplying the bare steel initiation values by 2.5.

Stainless Steel

Chloride threshold values for stainless steel have been reported to be at least 10.4 times greater than carbon steel (Clemeña, 2003).

MMFX-2 Steel

Several research projects have estimated the chloride threshold value for MMFX-2. The reported range of initiation values is 3.5 – 9.2 times that of carbon steel (Clemeña, 2003; Trejo, 2002). A conservative initiation value of 3.5 times that of carbon steel was used.

Service-Life Estimates

Using the adjusted chloride threshold values where appropriate, service-life estimates were performed for the above reinforcement alternatives. The estimates should provide a reasonable expectation of the time required for corrosion to initiate. It should also be noted that alternative reinforcements will have longer corrosion propagation times, which are not included in the service-life estimates presented below in Table 37.

Table 37. Service Life Predictions (Alternative Reinforcements)–A4 Concrete - $^{w}/_{cm}$ = 0.45

	Time to Initiation (years)			
Reinforcement Type	**Bare**	**Galvanized**	**Stainless**	**MMFX-2**
Time to 2% Initiation	160	602	9999	1312

As shown, bridge decks constructed using current bridge deck specifications (0.45 $^{w}/_{cm}$ and 2 in minimum cover depths) will in most cases never initiate corrosion within the desired service life of 100 years regardless of reinforcement type. Galvanized, stainless steel, and MMFX-2 reinforcement will provide a reliable second, redundant corrosion protection system where such systems are required.

Individual Deck Analysis

After validating the service life model and comparing the service life estimates of the three bridge deck sets the potential for the model to estimate the service life of an individual deck was investigated. The data collected for each individual bridge deck were used as input to the service life model and the results compared to actual field conditions. The input generally consisted of 9 C_o values, 9 D_{ca} values, and 40-80 cover depths, x values. The number of values for C_o and D_{ca} was lower in some instances due to missing or inconsistent data and the number of cover depth measurements was dependent upon the length of the deck.

The ability of the service life model to accurately estimate the service lives of individual bridge decks was first investigated using the 0.47 $^{w}/_{c}$ bridge deck data. The service life estimates for those ten bridge decks are presented in Table 38.

Table 38. 0.47 $^{w}/_{c}$ Bridge Deck Service Life Estimates – Individual

Structure #	% Damage	Time to Initiation 2% or Less (years)	Time to Corrosion Cracking	Propagation Time (years)	Estimated Age (years)	Actual Age (years)	Difference (years)
1-1804	5.3	13	6	6	25	37	12
1-6101	0.0	>100	6	----	----	37	----
2-2007	2.3	18	6	1	25	36	11
3-1021	0.2	11	6	----	17	35	18
4-1062	0.0	>100	6	----	----	37	----
4-2049	0.7	>100	6	----	100	38	-62
5-1800	3.3	>100	6	3	100	36	-64
6-1032	0.0	>100	6	----	----	35	----
9-2801	3.0	72	6	2	80	36	-44
9-6042	1.1	32	6	----	38	37	-1

As is evident in Table 38, the model is not capable of accurately estimating the service life for individual bridge decks on a consistent basis with the amount of data available. The model overestimates the service life in some cases and underestimates in others. It is believed that the models' inability to accurately predict the service lives of individual bridge decks is related to the quantity of input data. Low quantities of input data may not accurately represent the characteristics of the bridge decks. The parameter where this is most evident is D_{ca}. It is possible for an individual bridge deck to have a coefficient of variation in excess of 100% for D_{ca}. Therefore, the probability of 9 values being able to accurately define the distribution is low. Due to the observed inability of the model to predict the service lives of the 10 bridge decks investigated, any analysis of individual bridge decks should be viewed with some caution. The amount of model input data needed is suggested in the recommendation section.

Life Cycle Cost Comparison Examples

Several examples are presented below to illustrate the use of the LCC comparison tables.

Example 1:

Given: A maintenance strategy for a 30-year old bridge deck is to be selected in the current year (2008). 0.5% of the bridge deck is presently deteriorated in the worst span lane and the total desired service life of the bridge deck is 100 years. The ADT for the bridge is 30,000 and traffic control is to be considered.

Solution: An ADT of 30,000 is considered high when determining the maintenance schedule for the polymer overlays. Given that the bridge deck is 30 years old and the desired service life is 100 years, the required remaining service life is 70 years. Using Table 13 the LCCs are summed from year 0 – 70 for the two maintenance alternatives being investigated (values to be summed are highlighted in Table 39).

Summing the LCCs for the two maintenance alternatives over the 70-year period yields total LCCs of $141.70/SY and $213.90/SY for polymer overlays and concrete overlays, respectively. Therefore, the decision in this case would be to use polymer overlays to extend the service life of the bridge deck.

Example 2:

Given: The same bridge deck presented in Example 1 is to be considered. However, now the ADT is 60,000 and the required remaining service life is only 25 years.

Solution: The LCCs to be summed are highlighted in Table 40.

Summing the LCCs for the two maintenance alternatives over the 25-year period yields total LCCs of $129.70/SY and $125.41/SY for polymer overlays and concrete overlays, respectively. Therefore, the decision in this case would be to use concrete overlays to extend the service life of the bridge deck. However, since the difference between the two alternatives is small, the engineer may choose the higher cost alternative based on other extenuating circumstances.

Table 39. LCCA – Example 1

2008 With Traffic Control		Polymer Overlay ($/SY)			Concrete Overlay ($/SY)
		Average Daily Traffic (ADT)			
	Year	Very High	High	Moderate	
Required Remaining Service Life	0	47.83	47.83	47.83	0.00
	5				20.25
	10	46.94			17.46
	15		40.49		87.70
	20	34.93			
	25			30.13	
	30	25.99	25.99		9.67
	35				8.34
	40	19.34			41.88
	45		16.68		
	50	14.39		14.39	
	55				4.62
	60	10.71	10.71		3.98
	65				20.00
	70	7.97			
	Sum		141.69		213.91
	75		6.87	6.87	
	80	5.93			2.21
	85				1.90
	90	4.41	4.41		9.55
	95				
	100				
	Sum	218.42	294.67	99.22	441.48

* ADT: Moderate = 5,000 to 25,000; High => 25,000; Very High => 50,000
* Real Discount Rate – 3.00%

Example 3:

Given: A bridge deck is currently 20 years old and showing no signs of corrosion deterioration. Using measured chloride concentrations, and cover depths, engineers have estimated that the bridge deck will begin to reflect corrosion damage in approximately 20 years. The projected ADT of the bridge deck is 10,000 and the total desired service life is 80 years. Traffic control will not be considered.

Solution: Given that the maintenance strategy is not to be selected in the current year, but rather 20 years in the future, the Table for year 2028 will be used for the analysis. The ADT is considered moderate and at the time of analysis the bridge deck will be 40 years old. Therefore, the required remaining service life will be 40 years

As shown in Table 41, the total LCCs for the maintenance alternatives are $28.74/SY and $74.81/SY for polymer overlays and concrete overlays, respectively. Therefore, polymer overlays would be selected as the most cost effective alternative.

Example 4:

Given: A maintenance strategy for a 40-year old bridge deck is to be selected in the current year (2008). 4.0% of the bridge deck is presently deteriorated in the worst span lane and the total desired service life of the bridge deck is 100 years. The ADT for the bridge is 30,000 and traffic control is to be considered.

Table 40. LCCA – Example 2

2008 With Traffic Control		Polymer Overlay ($/SY)			Concrete Overlay ($/SY)
		Average Daily Traffic (ADT)			
	Year	Very High	High	Moderate	
Required Remaining Service Life	0	47.83	47.83	47.83	0.00
	5				20.25
	10	46.94			17.46
	15		40.49		87.70
	20	34.93			
	25			30.13	
	Sum	129.69			125.41
	30	25.99	25.99		9.67
	35				8.34
	40	19.34			41.88
	45		16.68		
	50	14.39		14.39	
	55				4.62
	60	10.71	10.71		3.98
	65				20.00
	70	7.97			
	75		6.87	6.87	
	80	5.93			2.21
	85				1.90
	90	4.41	4.41		9.55
	95				
	100				

* ADT: Moderate = 5,000 to 25,000; High => 25,000; Very High => 50,000
* Real Discount Rate – 3.00%

Solution: A LCCA is not required for this example because polymer overlays are not appropriate for bridge decks with total areas of corrosion deterioration greater than 1%. Therefore, concrete overlays should be selected as the maintenance alternative for this example.

Example 5:

Given: A bridge deck is reflecting between 0 and 1% corrosion deterioration in the worst span lane and a maintenance strategy is to be selected in the current year. Due to expected changes in traffic patterns the engineer is not able to accurately estimate future traffic loads. The engineer is also unsure of what the required service life of the bridge will be. Traffic control is to be considered.

Solution: Given the uncertainties in the problem the engineer can develop cash flow charts using the tabulated LCC data to investigate the sensitivity of the analysis to individual parameters. An example of a cash flow diagram for a bridge deck whose maintenance strategy is to be selected in the current year is presented in Figure 20.

Using the cash flow diagram presented above, the engineer can investigate the effects of varying traffic volumes on the selection of the appropriate maintenance strategy. As shown, polymer overlays are the most economical option in nearly all cases. Concrete overlays are more cost-effective only if the ADT is expected to be very high and the required remaining service life falls within certain time frames. Therefore, due to the uncertainty of the project the most economical alternative will most likely be polymer overlays.

Table 41. LCCA – Example 3

2028 Without Traffic Control		Polymer Overlay ($/SY) Average Daily Traffic (ADT)			Concrete Overlay ($/SY)
	Year	**Very High**	**High**	**Moderate**	
Required Remaining Service Life	0	16.72	16.72	16.72	0.00
	5				11.21
	10	18.72			9.67
	15		16.15		29.75
	20	13.93			
	25			12.02	
	30	10.37	10.37		5.35
	35				4.62
	40	7.71			14.21
	Sum			28.73	74.81
	45		6.65		
	50	5.74		5.74	
	55				2.56
	60	4.27	4.27		2.21
	65				6.79
	70	3.18			
	75		2.74	2.74	
	80	2.36			1.22
	85				1.05
	90	1.76	1.76		3.24
	95				
	100				

* ADT: Moderate = 5,000 to 25,000; High => 25,000; Very High => 50,000
* Real Discount Rate – 3.00%

Maintenance Planning Costs

The maintenance alternative decisions presented in the previous section were based upon total LCCs calculated using a discount rate of 3.0%. LCCAs are useful for determining the most cost-effective maintenance alternative for a given bridge deck. However, it is often the case that maintenance officials are interested in the total cost of a maintenance alternative. Knowing the total cost of an alternative is useful in that there are inherent risks when conducting LCCAs using estimated discount rates because if actual discount rates differ from estimated rates the resulting LCCs may vary substantially. By estimating the total inflated costs of maintenance alternatives the engineer can compare alternatives based upon total expected costs. These comparisons will be void of any benefit that is anticipated from saving money in the short-term. Additionally, by computing actual costs the engineer can estimate the number of dollars that will be required to maintain a bridge in any given year.

To estimate the total cost of a maintenance alternative, the project costs in future years must be inflated from costs in the current year. Costs were increased using an inflation rate of 3.0%, which was estimated for construction projects previously. The resulting inflated costs for maintenance strategy decisions to be made within the next 50 years are presented in Tables 42-53.

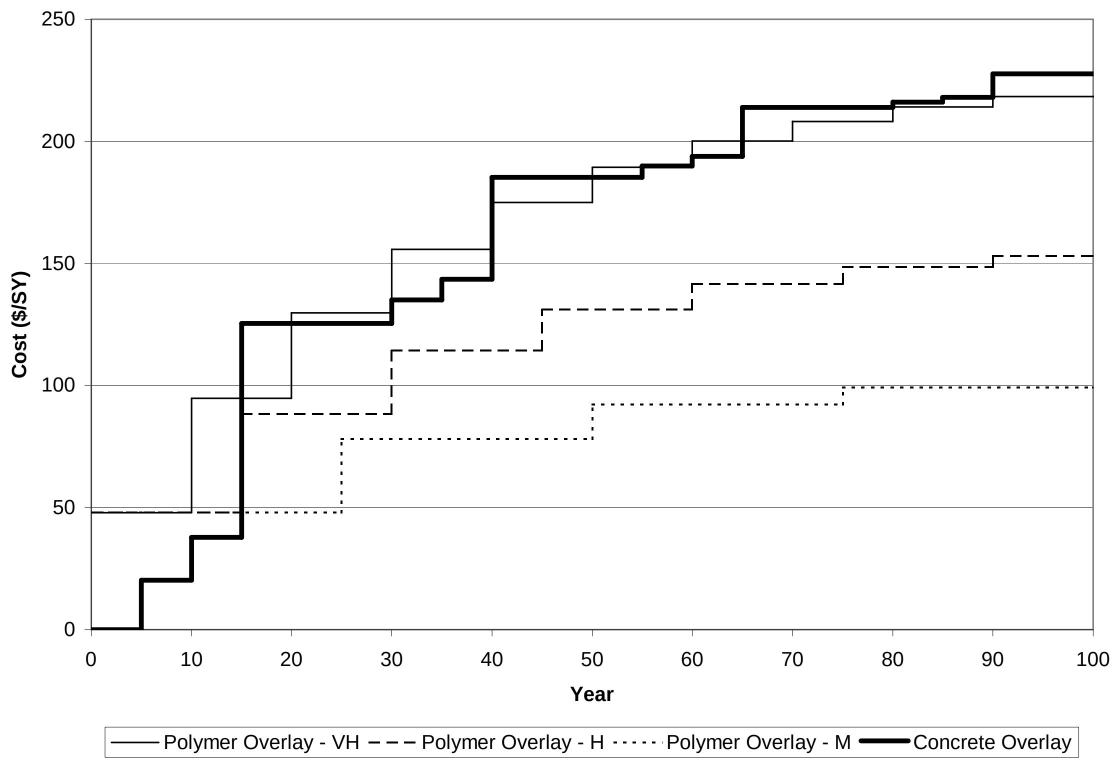

Figure 20. Cash Flow Diagram – Example 5

Future costs were calculated using the following time-value of money relationship:

$$FV = PV \times (1+i)^n \qquad \text{Equation 4}$$

where:

FV = Future Value
PV = Present Value
i = Inflation rate
n = Number of years in the future

Table 42. Inflated Cost Comparison – 2008 – Without TC

2008 Without Traffic Control		Polymer Overlay ($/SY)			Concrete Overlay ($/SY)
		Average Daily Traffic (ADT)			
Required Remaining Service Life	Year	Very High	High	Moderate	
	0	30.19	30.19	30.19	0.00
	5				27.21
	10	61.07			31.54
	15		70.79		130.42
	20	82.07			
	25			95.14	
	30	110.29	110.29		56.97
	35				66.04
	40	148.23			273.07
	45		171.84		
	50	199.20		199.20	
	55				119.28
	60	267.71	267.71		138.28
	65				571.74
	70	359.79			
	75		417.09	417.09	
	80	483.52			249.74
	85				289.52
	90	649.81	649.81		1,197.09
	95				
	100				

* ADT: Moderate = 5,000 to 25,000; High => 25,000; Very High => 50,000
* Real Discount Rate – 3.00%

Table 43. Inflated Cost Comparison – 2008 – With TC

2008 With Traffic Control		Polymer Overlay ($/SY)			Concrete Overlay ($/SY)
		Average Daily Traffic (ADT)			
Required Remaining Service Life	Year	Very High	High	Moderate	
	0	47.83	47.83	47.83	0.00
	5				27.21
	10	84.77			31.54
	15		98.28		212.87
	20	113.93			
	25			132.08	
	30	153.11	153.11		56.97
	35				66.04
	40	205.77			445.69
	45		238.54		
	50	276.54		276.54	
	55				119.28
	60	371.64	371.64		138.28
	65				933.18
	70	499.46			
	75		579.01	579.01	
	80	671.23			249.74
	85				289.52
	90	902.07	902.07		1,953.87
	95				
	100				

* ADT: Moderate = 5,000 to 25,000; High => 25,000; Very High => 50,000
* Real Discount Rate – 3.00%

Table 44. Inflated Cost Comparison – 2018 – Without TC

2018 Without Traffic Control		Polymer Overlay ($/SY)			Concrete Overlay ($/SY)
		Average Daily Traffic (ADT)			
	Year	Very High	High	Moderate	
Required Remaining Service Life	0	40.57	40.57	40.57	0.00
	5				36.57
	10	82.07			42.39
	15		95.14		175.27
	20	110.29			
	25			127.86	
	30	148.23	148.23		76.56
	35				88.75
	40	199.20			366.98
	45		230.93		
	50	267.71		267.71	
	55				160.30
	60	359.79	359.79		185.83
	65				768.37
	70	483.52			
	75		560.53	560.53	
	80	649.81			335.63
	85				389.09
	90	873.29	873.29		1,608.79
	95				
	100				

* ADT: Moderate = 5,000 to 25,000; High => 25,000; Very High => 50,000
* Real Discount Rate – 3.00%

Table 45. Inflated Cost Comparison – 2018 – With TC

2018 With Traffic Control		Polymer Overlay ($/SY)			Concrete Overlay ($/SY)
		Average Daily Traffic (ADT)			
	Year	Very High	High	Moderate	
Required Remaining Service Life	0	64.28	64.28	64.28	0.00
	5				36.57
	10	113.93			42.39
	15		132.08		286.07
	20	153.11			
	25			177.50	
	30	205.77	205.77		76.56
	35				88.75
	40	276.54			598.97
	45		320.58		
	50	371.64		371.64	
	55				160.30
	60	499.46	499.46		185.83
	65				1,254.12
	70	671.23			
	75		778.14	778.14	
	80	902.07			335.63
	85				389.09
	90	1,212.31	1,212.31		2,625.84
	95				
	100				

* ADT: Moderate = 5,000 to 25,000; High => 25,000; Very High => 50,000
* Real Discount Rate – 3.00%

Table 46. Inflated Cost Comparison – 2028 – Without TC

2028 Without Traffic Control		Polymer Overlay ($/SY)			Concrete Overlay ($/SY)
		Average Daily Traffic (ADT)			
	Year	Very High	High	Moderate	
Required Remaining Service Life	0	54.53	54.53	54.53	0.00
	5				49.14
	10	110.29			56.97
	15		95.14		235.55
	20	148.23			
	25			171.84	
	30	199.20	199.20		102.89
	35				119.28
	40	267.71			493.19
	45		310.35		
	50	359.79		359.79	
	55				215.43
	60	483.52	483.52		249.74
	65				1,032.62
	70	649.81			
	75		753.31	753.31	
	80	873.29			451.06
	85				522.90
	90	1,173.63	1,173.63		2,162.08
	95				
	100				

* ADT: Moderate = 5,000 to 25,000; High => 25,000; Very High => 50,000
* Real Discount Rate – 3.00%

Table 47. Inflated Cost Comparison – 2028 – With TC

2028 With Traffic Control		Polymer Overlay ($/SY)			Concrete Overlay ($/SY)
		Average Daily Traffic (ADT)			
	Year	Very High	High	Moderate	
Required Remaining Service Life	0	86.39	86.39	86.39	0.00
	5				49.14
	10	153.11			56.97
	15		177.50		384.46
	20	205.77			
	25			238.54	
	30	276.54	276.54		102.89
	35				119.28
	40	371.64			804.97
	45		430.84		
	50	499.46		499.46	
	55				215.43
	60	671.23	671.23		249.74
	65				1,685.43
	70	902.07			
	75		1,045.75	1045.75	
	80	1,212.31			451.06
	85				522.90
	90	1,629.25	1,629.25		3,528.91
	95				
	100				

* ADT: Moderate = 5,000 to 25,000; High => 25,000; Very High => 50,000
* Real Discount Rate – 3.00%

Table 48. Inflated Cost Comparison – 2038 – Without TC

2038 Without Traffic Control		Polymer Overlay ($/SY)			Concrete Overlay ($/SY)
		Average Daily Traffic (ADT)			
	Year	Very High	High	Moderate	
Required Remaining Service Life	0	73.28	73.28	73.28	0.00
	5				66.04
	10	148.23			76.56
	15		171.84		316.56
	20	199.20			
	25			230.93	
	30	267.71	267.71		138.28
	35				160.30
	40	359.79			662.80
	45		417.09		
	50	483.52		483.52	
	55				289.52
	60	649.81	649.81		335.63
	65				1,387.76
	70	873.29			
	75		1,012.39	1,012.39	
	80	1,173.63			606.19
	85				702.74
	90	1,577.27	1,577.27		2,905.66
	95				
	100				

* ADT: Moderate = 5,000 to 25,000; High => 25,000; Very High => 50,000
* Real Discount Rate – 3.00%

Table 49. Inflated Cost Comparison – 2038 – With TC

2038 With Traffic Control		Polymer Overlay ($/SY)			Concrete Overlay ($/SY)
		Average Daily Traffic (ADT)			
	Year	Very High	High	Moderate	
Required Remaining Service Life	0	116.10	116.10	116.10	0.00
	5				66.04
	10	205.77			76.56
	15		238.54		516.68
	20	276.54			
	25			320.58	
	30	371.64	371.64		138.28
	35				160.30
	40	499.46			1,081.81
	45		579.01		
	50	671.23		671.23	
	55				289.52
	60	902.07	902.07		335.63
	65				2,265.07
	70	1,212.31			
	75		1,405.40	1,405.40	
	80	1,629.25			606.19
	85				702.74
	90	2,189.57	2,189.57		4,742.56
	95				
	100				

* ADT: Moderate = 5,000 to 25,000; High => 25,000; Very High => 50,000
* Real Discount Rate – 3.00%

Table 50. Inflated Cost Comparison – 2048 – Without TC

2048 Without Traffic Control		Polymer Overlay ($/SY)			Concrete Overlay ($/SY)
		Average Daily Traffic (ADT)			
	Year	Very High	High	Moderate	
Required Remaining Service Life	0	98.48	98.48	98.48	0.00
	5				88.75
	10	199.20			102.89
	15		230.93		425.43
	20	267.71			
	25			310.35	
	30	359.79	359.79		185.83
	35				215.43
	40	483.52			890.75
	45		560.53		
	50	649.81		649.81	
	55				389.09
	60	873.29	873.29		451.06
	65				1,865.03
	70	1,173.63			
	75		1,360.56	1,360.56	
	80	1,577.27			814.67
	85				944.42
	90	2,119.72	2,119.72		3,904.96
	95				
	100				

* ADT: Moderate = 5,000 to 25,000; High => 25,000; Very High => 50,000
* Real Discount Rate – 3.00%

Table 51. Inflated Cost Comparison – 2048 – With TC

2048 With Traffic Control		Polymer Overlay ($/SY)			Concrete Overlay ($/SY)
		Average Daily Traffic (ADT)			
	Year	Very High	High	Moderate	
Required Remaining Service Life	0	156.02	156.02	156.02	0.00
	5				88.75
	10	276.54			102.89
	15		320.58		694.37
	20	371.64			
	25			430.84	
	30	499.46	499.46		185.83
	35				215.43
	40	671.23			1,453.86
	45		778.14		
	50	902.07		902.07	
	55				389.09
	60	1,212.31	1,212.31		451.06
	65				3,044.07
	70	1,629.25			
	75		1,888.74	1,888.74	
	80	2,189.57			814.67
	85				944.42
	90	2,942.60	2,942.60		6,373.61
	95				
	100				

* ADT: Moderate = 5,000 to 25,000; High => 25,000; Very High => 50,000
* Real Discount Rate – 3.00%

Table 52. Inflated Cost Comparison – 2058 – Without TC

2058 Without Traffic Control		Polymer Overlay ($/SY)			Concrete Overlay ($/SY)
		Average Daily Traffic (ADT)			
	Year	Very High	High	Moderate	
Required Remaining Service Life	0	132.35	132.35	132.35	0.00
	5				119.28
	10	267.71			138.28
	15		310.35		571.74
	20	359.79			
	25			417.09	
	30	483.52	483.52		249.74
	35				289.52
	40	649.81			1,197.09
	45		753.31		
	50	873.29		873.29	
	55				522.90
	60	1,173.63	1,173.63		606.19
	65				2,596.45
	70	1,577.27			
	75		1,828.49	1,828.49	
	80	2,119.72			1,094.84
	85				1,269.22
	90	2,848.72	2,848.72		5,247.94
	95				
	100				

* ADT: Moderate = 5,000 to 25,000; High => 25,000; Very High => 50,000
* Real Discount Rate – 3.00%

Table 53. Inflated Cost Comparison – 2058 – With TC

2058 With Traffic Control		Polymer Overlay ($/SY)			Concrete Overlay ($/SY)
		Average Daily Traffic (ADT)			
	Year	Very High	High	Moderate	
Required Remaining Service Life	0	209.68	209.68	209.68	0.00
	5				119.28
	10	371.64			138.28
	15		430.84		933.18
	20	499.46			
	25			579.01	
	30	671.23	671.23		249.74
	35				289.52
	40	902.07			1,953.87
	45		671.23		
	50	1,212.31		1,212.31	
	55				522.90
	60	1,629.25	1,629.25		606.19
	65				4,090.98
	70	2,189.57			
	75		2,538.31	2,538.31	
	80	2,942.60			1,094.84
	85				1,269.22
	90	3,954.61	3,954.61		8,565.59
	95				
	100				

* ADT: Moderate = 5,000 to 25,000; High => 25,000; Very High => 50,000
* Real Discount Rate – 3.00%

The maintenance planning costs presented in Tables 42-53 were derived from the maintenance activity timings presented in Table 54. These maintenance activities are the same as those used in the previous LCCA examples.

Inflated Cost Comparison Examples

The examples presented in the LCCA section are revisited below to compare decisions based upon LCCA methodology and total cost methodology.

Example 1:

Given: A maintenance strategy for a 30-year old bridge deck is to be selected in the current year (2008). 0.5% of the bridge deck is presently deteriorated in the worst span lane and the total desired service life of the bridge deck is 100 years. The ADT for the bridge is 30,000 and traffic control is to be considered.

Solution: An ADT of 30,000 is considered high when determining the maintenance schedule for the polymer overlays. Given that the bridge deck is 30 years old and the desired service life is 100 years, the required remaining service life is 70 years. Using Table 43 the inflated costs are summed from year 0 – 70 for the two maintenance alternatives being investigated (values to be summed are highlighted in Table 55).

Table 54. Maintenance Activity Timings – Total Costs

Year	Polymer Overlays ADT			Concrete Overlays
	VH	H	M	
0	PO and 1% P	PO and 1% P	PO and 1% P	
5				6% P
10	OR, PO and 1% P			6% P
15		OR, PO and 1% P		M, CO and G
20	OR, PO and 1% P			
25			OR, PO and 1% P	
30	OR, PO and 1% P	OR, PO and 1% P		6% P
35				6% P
40	OR, PO and 1% P			M, CO and G
45		OR, PO and 1% P		
50	OR, PO and 1% P		OR, PO and 1% P	
55				6% P
60	OR, PO and 1% P	OR, PO and 1% P		6% P
65				M, CO and G
70	OR, PO and 1% P			
75		OR, PO and 1% P	OR, PO and 1% P	
80	OR, PO and 1% P			6% P
85				6% P
90	OR, PO and 1% P	OR, PO and 1% P		M, CO and G
95				
100				

*PO = Polymer Overlay; P = Patching; OR = Overlay Removal; M = Milling;
CO = Concrete Overlay; G = Bridge Deck Grooving

Summing the inflated costs for the two maintenance alternatives over the 70-year period yields total inflated costs of $909.40/SY and $2031.05/SY for polymer overlays and concrete overlays, respectively. Therefore, the decision in this case would be to use polymer overlays to extend the service life of the bridge deck. As shown, the maintenance alternative recommendation does not change when the total inflated costs are considered in place of the total LCCs for this example.

Example 2:

Given: The same bridge deck presented in Example 1 is to be considered. However, now the ADT is 60,000 and the required remaining service life is only 25 years.

Solution: The inflated costs to be summed are highlighted in Table 56.

Table 55. Inflated Costs – Example 1

2008 With Traffic Control		Polymer Overlay ($/SY)			Concrete Overlay ($/SY)
		Average Daily Traffic (ADT)			
Required Remaining Service Life	Year	Very High	High	Moderate	
	0	47.83	47.83	47.83	0.00
	5				27.21
	10	84.77			31.54
	15		98.28		212.87
	20	113.93			
	25			132.08	
	30	153.11	153.11		56.97
	35				66.04
	40	205.77			445.69
	45		238.54		
	50	276.54		276.54	
	55				119.28
	60	371.64	371.64		138.28
	65				933.18
	70	499.46			
	Sum		909.40		2,031.05
	75		579.01	579.01	
	80	671.23			249.74
	85				289.52
	90	902.07	902.07		1,953.87
	95				
	100				

* ADT: Moderate = 5,000 to 25,000; High => 25,000; Very High => 50,000
* Real Discount Rate – 3.00%

Summing the inflated costs for the two maintenance alternatives over the 25-year period yields total inflated costs of $246.53/SY and $271.61/SY for polymer overlays and concrete overlays, respectively. Therefore, the decision in this case would be to use polymer overlays to extend the service life of the bridge deck. Thus, $25.08/SY of bridge deck would be saved. This money could then be invested into transportation-related research projects or other required maintenance activities. In this example, using the total inflated costs resulted in a different recommendation as compared to the same example using LCCA. This is due to the specific timings and magnitudes of the maintenance activities presented.

Table 56. Inflated Costs – Example 2

2008 With Traffic Control		Polymer Overlay ($/SY) Average Daily Traffic (ADT)			Concrete Overlay ($/SY)
Required Remaining Service Life	Year	Very High	High	Moderate	
	0	47.83	47.83	47.83	0.00
	5				27.21
	10	84.77			31.54
	15		98.28		212.87
	20	113.93			
	25			132.08	
	Sum	246.53			271.61
	30	153.11	153.11		56.97
	35				66.04
	40	205.77			445.69
	45		238.54		
	50	276.54		276.54	
	55				119.28
	60	371.64	371.64		138.28
	65				933.18
	70	499.46			
	75		579.01	579.01	
	80	671.23			249.74
	85				289.52
	90	902.07	902.07		1,953.87
	95				
	100				

* ADT: Moderate = 5,000 to 25,000; High => 25,000; Very High => 50,000
* Real Discount Rate – 3.00%

Example 3:

Given: A bridge deck is currently 20 years old and showing no signs of corrosion deterioration. Using measured chloride concentrations, and cover depths, engineers have estimated that the bridge deck will begin to reflect corrosion damage in approximately 20 years. The projected ADT of the bridge deck is 10,000 and the total desired service life is 80 years. Traffic control will not be considered.

Solution: Given that the maintenance strategy is not to be selected in the current year, but rather 20 years in the future, the Table for year 2028 will be used for the analysis. The ADT is considered moderate and at the time of analysis the bridge deck will be 40 years old. Therefore, the required remaining service life will be 40 years.

As shown in Table 57, the total inflated costs for the maintenance alternatives are $226.37/SY and $1057.02/SY for polymer overlays and concrete overlays, respectively. Therefore, polymer overlays would be selected as the most cost effective alternative.

Example 4:

Given: A maintenance strategy for a 40-year old bridge deck is to be selected in the current year (2008). 4.0% of the bridge deck is presently deteriorated in the worst span lane and the total desired service life of the bridge deck is 100 years. The ADT for the bridge is 30,000 and traffic control is to be considered.

Table 57. Inflated Costs – Example 3

2028 Without Traffic Control		Polymer Overlay ($/SY)			Concrete Overlay ($/SY)
		Average Daily Traffic (ADT)			
	Year	Very High	High	Moderate	
Required Remaining Service Life	0	54.53	54.53	54.53	0.00
	5				49.14
	10	110.29			56.97
	15		95.14		235.55
	20	148.23			
	25			171.84	
	30	199.20	199.20		102.89
	35				119.28
	40	267.71			493.19
	Sum			226.36	1,057.01
	45		310.35		
	50	359.79		359.79	
	55				215.43
	60	483.52	483.52		249.74
	65				1,032.62
	70	649.81			
	75		753.31	753.31	
	80	873.29			451.06
	85				522.90
	90	1,173.63	1,173.63		2,162.08
	95				
	100				

* ADT: Moderate = 5,000 to 25,000; High => 25,000; Very High => 50,000
* Real Discount Rate – 3.00%

Solution: A total maintenance cost analysis is not required for this example because polymer overlays are not appropriate for bridge decks with total areas of corrosion deterioration greater than 1%. Therefore, concrete overlays should be selected as the maintenance alternative for this example.

Example 5:

Given: A bridge deck is reflecting between 0 and 1% corrosion deterioration in the worst span lane and a maintenance strategy is to be selected in the current year. Due to expected changes in traffic patterns the engineer is not able to accurately estimate future traffic loads. The engineer is also unsure of what the required service life of the bridge will be. Traffic control is to be considered.

Solution: Given the uncertainties in the problem the engineer can develop cash flow charts using the tabulated inflated cost data to investigate the sensitivity of the analysis to individual parameters. An example of a cash flow diagram for a bridge deck whose maintenance strategy is to be selected in the current year is presented in Figure 21.

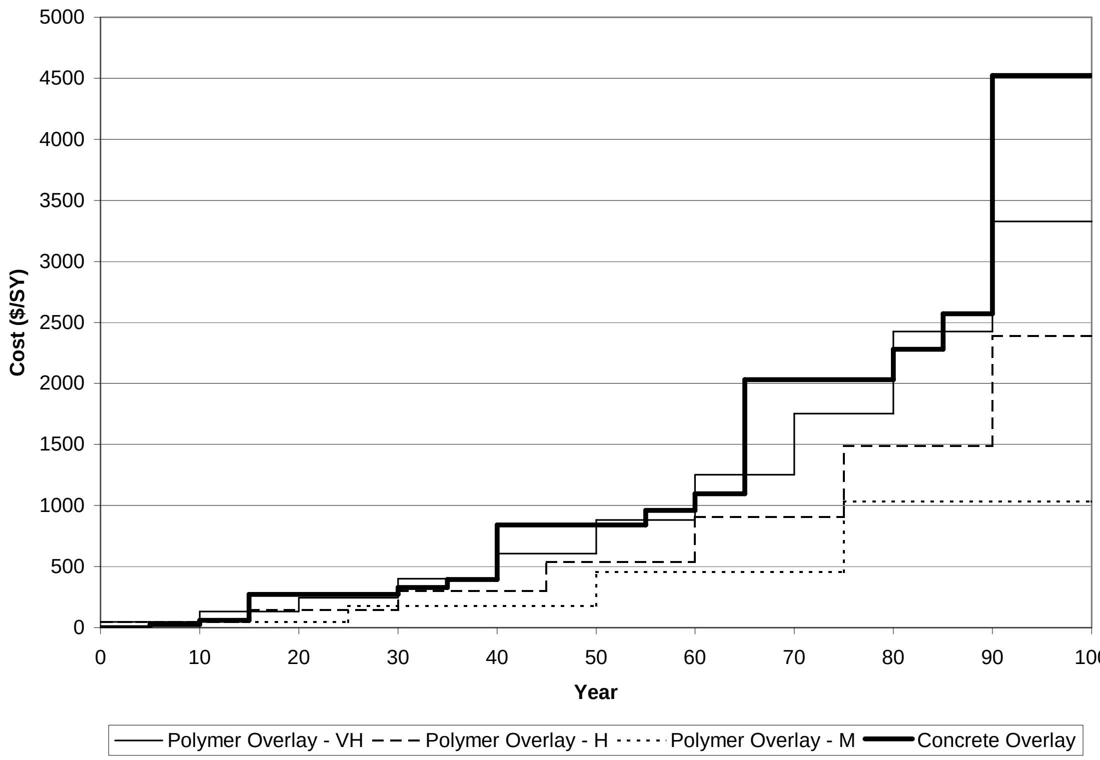

Figure 21. Cash Flow Diagram – Inflated Costs – Example 5

Using the cash flow diagram presented above, the engineer can investigate the effects that varying traffic volumes will have on the selection of the appropriate maintenance strategy. As shown, polymer overlays are the most economical option in nearly all cases. Concrete overlays are more cost-effective only if the ADT is expected to be very high and the required remaining service life falls within certain time frames. Therefore, due to the uncertainty of the project the most economical alternative will most likely be polymer overlays. It is important to note that this total cost analysis results in the same recommendations as the LCCA.

The total cost approach is not expected to affect the maintenance alternative selected in most cases. However, it will provide useful data concerning the anticipated costs to be incurred in the future. By knowing the timings and amounts of future maintenance expenditures the engineer can better plan and budget maintenance activities.

Table 58 presents the LCCA and Total Inflated Costs that were calculated for Examples 1 – 3. As shown, the maintenance alternative selected remained the same for Examples 1 and 3, regardless of the analysis method. The recommended maintenance alternative changed for Example 2, however, the argument can be made that the cost difference computed for LCCA method is so minute that either maintenance alternative could be selected.

Table 58. LCCA/Total Inflated Cost Comparison

Methodology		Example 1		Example 2		Example 3	
		Polymer	Concrete	Polymer	Concrete	Polymer	Concrete
Cost/SY	LCCA	141.70	213.90	129.70	125.41	28.74	74.81
	Total Inflated Cost	909.40	2,031.06	246.53	271.62	226.37	1,057.02

CONCLUSIONS

The project conclusions are as follows:

- The time to first repair and rehabilitation of bridge decks can be modeled using a probabilistic approach, which allows for the incorporation of variability related to chloride exposure conditions, bridge deck construction, and corrosion initiation.

- Fick's second law of diffusion can be used to model the apparent diffusion rate of chlorides into a concrete bridge deck. Additionally, the effective diffusion rate at any point in time can be projected using available diffusion decay models.

- The time required for corrosion to induce cracking in the cover concrete can be estimated using existing corrosion-cracking models. An estimated time to corrosion cracking of 6 years for bare steel reinforcement was determined for this study.

- A reasonable estimate of the time required for corrosion deterioration to progress from a level of 2% to a level of 12% was determined from damage surveys conducted on actively corroding bridge decks. The corrosion propagation time for bare steel bridge decks is estimated to be 16 years.

- The reduction of the $^{w}/_{c}$ ratio from 0.47 to 0.45 appears to have a negligible effect on the diffusion properties of the sampled bridge deck concrete.

- The addition of fly ash or slag to the sampled bridge deck concrete mixture appears to dramatically reduce the diffusion rate of chlorides into concrete and have equivalent long term corrosion protection effects.

- The service lives of bridge decks constructed under current specifications (0.45 $^{w}/_{cm}$ and 2 in cover depth) are expected to exceed a design life of 100 years regardless of reinforcement type.

- Surface chloride concentrations, C_o, have been determined for the Commonwealth of Virginia and are only a function of the environmental exposure conditions not the type of concrete.

- Apparent diffusions, D_{ca}, have been determined for the Commonwealth of Virginia for $^w/_c$ = 0.47, $^w/_c$ = 0.45 and $^w/_{cm}$ = 0.45 bridge deck concrete and may be used in estimating the rate of corrosion damage to bridge decks within the Commonwealth of Virginia.

- The rate of deterioration of populations of bridge decks built under different state wide specifications may be determined using the probability based chloride diffusion model, plus the time to cracking of 6 years, plus the propagation period of 16 years for 2% to 12% damage of the worst span lane.

- The diffusion model plus the time to cracking and propagation periods may be used to predict the rate of corrosion damage for individual decks provided sufficient input data is provided. Model data requirements are provided in the recommendations section of the report.

- Life Cycle Costs Analyses can be conducted to determine optimum maintenance strategies for individual bridge decks.

- It is not appropriate to specify a single maintenance strategy for all bridge decks within a system, as the most economical alternative will be dependent upon individual structure parameters.

- Long-term inflation rates associated with transportation-related construction appear to correspond with the inflation rate of the general economy.

- A total maintenance cost approach to maintenance strategy selection generally results in the same conclusions as a LCCA approach.

RECOMMENDATIONS

The following recommendations to be addressed by the Structures and Bridge Division:

- It is recommended that newly constructed bridge decks be built under current specifications with bare steel reinforcement. The decision to use bare steel reinforcement over available alternative reinforcements was made based upon the determination that the service lives of bridge decks constructed under current cover depth and low permeable concrete specifications are expected to exceed 100 years regardless of reinforcement type. Therefore, reinforcement type should be selected on a first-cost basis. Bare steel being the least costly alternative would typically be the reinforcement of choice. However, alternative reinforcements such as stainless steel, stainless steel clad, or MMFX-2 may be used in place of bare steel as a secondary corrosion protection method for extreme chloride exposures or where a redundant corrosion protection system is required by FHWA.

- Life Cycle Cost Analyses should be conducted to determine the most economical maintenance alternative for individual bridge decks. Real discount rates provided by the Office of Management and Budget should be used to discount future expenditures.

(OMB, 2007) It is also recommended that the engineer account for costs incurred by the traveling public (User costs) as well as Agency costs in order to provide the most economical alternative to the public as a whole.

- The probability based chloride deterioration model and its associated computer software is to be used to determine the rate of corrosion damage of bridge decks. Polymer concrete overlays may be scheduled when the damage level is predicted to be between 0.5 and 1% damage. Otherwise, a concrete overlay is to be scheduled when the damage level of the worst span lane is between 10 and 12%.

- The chloride diffusion coefficients, D_{ca}, presented in Appendix A may be used in the probability model computer program for concrete bridge decks built with w/c = 0.47, w/c = 0.45, and w/cm = 0.45. Should more exact values be needed, the following sampling rate is recommended.

  Number of D_{ca} values = 20 + (L-150/7) Equation 5

  Where:
  L = length of the bridge deck in feet.

  A minimum of 5 chloride concentrations at various depths, including the surface chloride concentration, Co, are required to determine the apparent diffusion coefficient using the computer program. An additional value is needed to determine the chloride background concentration. A depth of 3 to 4 inches is normally sufficient for the background chloride concentration. Background values are to be subtracted from the 5 chloride concentrations values at various depths prior to calculating the diffusion coefficient.

- Service life estimates of specific bridge decks require cover depth measurements and surface chloride concentrations. The number of surface chloride concentrations is to be determined using equation 5. Surface chloride samples are to be from 0.25 to 0.75 in below the surface of the bridge deck concrete. The number of cover depth measurements are to be determined as follows:

  Number of cover depths = 40 + (L-20/3) Equation 6

- Measurements and samples are to be taken from the critical failure zone of the bridge deck and equally distributed throughout the length of the deck in non-damaged areas. Critical failure zone is typically the right traffic lane wheel path areas. Damage is defined as spalled, delaminated, and patch areas (asphalt or concrete). Thus, a damage condition survey is to be performed prior to cover depth measurements and chloride sampling.

- At least one 4 inch diameter core, 4 to 5 inches in length and not containing any reinforcing is to be taken for petrographic analysis to determine if the concrete contains fly ash or slag.

COSTS AND BENEFITS

The cost to implement the recommendations is variable depending on the bridge deck size and location. For an average bridge deck, 200 feet long and 40 feet wide, a two person crew can complete the field survey work in one day. Laboratory work, petrographic analysis of one core would be about $200 dollars and each powdered chloride concentration measurement is about $75.00. Thus, for an average bridge deck where only the surface chloride concentrations are needed, the total laboratory cost would be $2025.00. The two-person crew for one day would be about $1,440.00. Computer and engineering time is estimated at 2 hours or about $300.00. Thus, the total cost per average bridge deck is estimated at $3,665.00 plus travel expenses and traffic control.

Benefits are as follows:

- Cost savings to VDOT through optimum scheduling of bridge deck maintenance work.
- Cost savings to VDOT through the optimum selection of polymer concrete and concrete overlay maintenance work.
- Cost savings to users through minimizing delays and accidents.

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APPENDIX A: DIFFUSION COEFFICIENTS, mm^2/yr

w/c = 0.47

Bridge

1804: 27.12, 31.22, 48.95, 40.85, 48.48, 53.21, 20.25, 29.04, 22.46

6106: 990, 2.36, 8.42, 1.89, 4.12, 3.57, 4.73, 3.01, 2.98,

2007: 8.97, 13.55, 8.69, 2.30, 4.54, 7.80, 1.07, 4.99, 4.79,

1021: 39.96, 23.57, 21.49, 25.65, 5.42, 43.52, 8.22, 9.10, 9.18,

1062: 1.93, 5.32, 7.55, 4.59, 2.70, 1.18, 4.73, 1.02,

2049: 7.12, 7.95, 17.25, 6.05, 5.09, 7.74, 1.64, 1.89,

1800: 1.30, 11.99, 23.73, 4.24, 5.06, 1.52

1032: 1.57, 5.35, 2.55, 3.30, 5.64, 6.77, 7.73, 6.01,

2801: 8.92, 2.02, 3.34, 1.07, 4.05, 17.48, 1.01, 2.72, 1.79

6042: 6.04, 14.79, 13.45, 3.54, 21.09, 18.20, 14.26

w/c = 0.45

Bridge

1132: 36.81, 25.84, 38.40, 37.55, 42.66, 42.69, 26.50, 55.62,

1133: 151.8, 32.9, 75.1, 89.0, 68.2, 194.7, 36.9, 32.0, 63.1,

2820: 16.88, 13.78, 9.33, 13.29, 19.93, 36.59, 4.48, 4.48,

6051: 16.3, 40.8, 106.0, 54.1, 94.3, 56.0, 15.2, 18.7, 64.0,

1020: 16.49, 29.96, 1.55, 19.18, 19.22, 31.89, 6.56, 17.46, 15.58,

1003: 69.84, 26.63, 58.79, 37.56, 24.24, 15.48, 33.44,

1007: 41.4, 61.3, 10.9, 19.6, 6.5, 15.7, 34.7, 29.8, 18.4,

2901: 58.29, 29.44, 14.05, 10.57, 23.87, 33.58, 25.50, 32.51, 8.04,

w/c = 0.45

Bridge

2547: 12.07, 7.25, 7.16, 6.30, 4.96, 4.90, 1.30, 3.80, 2.04,

1920: 59.71, 59.04, 11.68, 36.93, 21.48, 50.83, 50.71, 32.85,

1019: 21.11, 30.15, 57.74, 22.37, 28.52, 39.04, 21.35, 18.88, 37.05,

1133: 22.03, 51.37, 65.75, 10.46, 22.14, 9.86, 15.39, 7.39, 12.18,

1014: 11.1, 10.3, 26.0, 15.9, 27.9, 26.2, 6.9, 45.1, 8.3,

1031: 27.09, 38.78, 43.57, 52.38, 24.57, 42.88, 54.47, 35.08, 12.53,

1098: 16.9, 7.8, 11.2, 6.7, 6.8, 6.2,

1139: 17.79, 20.33, 60.07, 33.52, 56.98, 16.48, 22.91, 48.81, 91.97,

w/cm = 0.45

Bridge

1152: 2.37, 1.74, 2.78, 2.62, 1.99,

2815: 1.74, 1.66, 3.97, 1.57, 1.47, 13.88, 2.49, 3.11,

2819: 3.14, 3.72, 3.82, 1.09, 2.85, 2.65, 4.28, 0.45, 0.44,

1021: 4.18, 6.22, 1.16, 1.87, 7.02, 0.50,

2812: 4.89, 3.61, 5.92, 5.96, 13.27, 4.86, 3.31, 9.32,

1002: 4.83, 1.39, 1.61, 2.06, 21.72, 5.11, 1.78, 4.51, 2.82,

1042: 4.35, 6.64, 7.62, 2.27, 11.23, 2.52, 8.68,

1002: 6.25, 16.54, 31.02, 7.27, 7.64, 4.68, 6.27, 15.27, 11.46,

6058: 10.64, 4.69, 7.29, 3.91, 7.91, 7.58, 8.65, 7.33, 5.57