Deck Performance Model Feasibility Study

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16. Abstract The MDT Research Bureau, in conjunction with the Bridge Bureau, conducted a feasibility study to report on the possible purchase or development of a bridge deck rehabilitation analysis system, possibly software, to improve the accuracy and cost-efficiency of the analysis process. The desired system would use life cycle cost analysis to determine the best deck repair/replace option, as well as the optimum timing of the work. A literature search of possible models or systems was done, but no appropriate systems were found. The state of the art was reviewed, and it was concluded that such a system could be developed in a manner that would have an excellent benefit:cost ratio.		
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FINAL REPORT

1.0 EXECUTIVE SUMMARY

Earth Tech Inc. (ETI) was retained by the Montana Department of Transportation (MDT) to perform a feasibility study to investigate the possibility of finding or developing a bridge deck rehab analysis tool for use in assessing deck repair options by least life cycle cost. The purpose was to save money by improving the efficiency and accuracy of the bridge deck rehabilitation assessment process. With Montana's large inventory of 4,700 bridges, there is potential for substantial cost savings.

The purpose of this project was not to assess the theoretical merits of all types of performance models, but only to identify the options that were most compatible and best suited to fulfill some special MDT bridge management needs as identified by their engineering staff. The MDT project committee provided guidance, and their bridge management policies were studied to clarify the technical as well as other needs and objectives. Cost and potential benefits would be two important criteria, along with accuracy, user-friendliness, and any special constraints and limitations.

A literature search was carried out to clarify the current state of the art, and bridge management systems were also studied since they contain valuable ideas, concepts or principles from their project level sub-modules. Initially the literature search was intended to find models to be rated for conformance to MDT needs and objectives. In actuality, the models were found to be unsuited for rating. In general, they contained intellectual property, which could be used to construct a model or assessment tool meeting MDT needs. The focus of this project was more practical than theoretical, so it was not our intention to present or debate the mathematics behind these models.

A user survey of other DOT's was conducted in an attempt to provide additional information on the state of the art, especially regarding non-reported systems in use by MDT's bridge assessment peers. Questionnaires were sent to a total of 35 North American DOT's to identify possible models and to get input on the pros and cons from other users. We also attempted to use this survey to identify practical issues to assist in rating the models, but few responses were received. The consensus was that there is no existing model or commercially available proprietary system that would solve MDT's needs and objectives.

The proposed project methodology was to use the information from the literature search on overall model knowledge to recommend some possible systems in different price ranges. Further analysis was done to identify the necessary features and/or models that could be used for that purpose. Several alternative systems, varying in cost and performance, were presented. The approximate benefits, as well as the development and implementation costs of these several systems were assessed. Based on this information it was concluded that a system meeting the needs and objectives of MDT could be developed.

2.0 INTRODUCTION

In MDT's request for proposals of Sept. 2001, MDT identified the possible need for a deck life prediction tool for individual bridge or program level analysis. Cost-effective bridge repair decision-making is enhanced by the ability to predict deterioration rates and the optimum timing of future preventive/rehabilitation/ replacement activities. ETI was retained by MDT to perform a feasibility study to investigate the possibility of purchasing or developing a bridge deck rehabilitation analysis tool for use in assessing possible repair options by least life cycle cost. This project involves an assessment of the probable costs and necessary features of such a tool. This tool is not to be confused with a bridge management system, which MDT already has in Pontis. MDT currently uses Pontis to store inventory and condition data. Pontis contains some service life prediction capability, but being visually based, Pontis does not have the required accuracy for use in project level analysis. Bridge deck deterioration is common to many jurisdictions around the world, and much research on related aspects has recently been done, so the project included a literature survey.

2.1 PURPOSE

The purpose of this project was to investigate the feasibility of developing/purchasing and using a project level, deck rehabilitation assessment tool. It was hoped to find a tool to assist engineers in accurate assessment of existing decks. The tool would address MDT's most common deck problem, corrosion-related deterioration, and would include a service life prediction model and life cycle cost analysis features. Being driven by deck testing data, the model should have greater accuracy than those of visually based network level management systems, such as Pontis. It should be able to identify the limits, in terms of MDT's bridge condition test data, for effectively scheduling certain types of repair.

2.2 BACKGROUND

Like many jurisdictions, Montana constructed much of its bridge inventory during the 60's, 70's and 80's. As the rate of system expansion has declined, the emphasis on optimizing the service life of existing bridges has increased. The general trend has switched from a purely safety-based approach of systems and methods to a combination of safety-based and life cycle cost approach, i.e. giving more consideration to long-term planning and lowest long-term costs. Chloride-induced corrosion, which creates surface spalling, is the primary problem facing the heavily traveled portion of Montana's bridges. Many new repair methods are available, and the need to compare the costs of alternate methods has increased. Repairs are being engineered to meet site conditions. The impact of repair timing on the service life gained is being recognized. Increased speed limits and traffic counts are requiring greater amounts of chloride-based de-icing chemicals being applied to decks to shorten their service lives. The underlying reason for considering the development of a deck life model is to improve the efficiency of repairs and reduce overall system costs.

Montana's 4,700 bridges have a replacement value of about $2.5 billion. The average bridge age is about 35 years, with half being older. The bridges are located in a variety of climatic conditions. Western Montana bridges are generally at higher elevation, exposed to more moisture, snowfall and freeze-thaw cycles than the eastern ones. Of the total inventory, only about a thousand bridges are exposed to relatively high levels of chlorides from roadway de-icing/anti-icing chemicals, which promote deck problems. Many of these bridges are on the US interstate system, which was mostly constructed during a limited time period and is now aging. For these more rapidly deteriorating bridges, which have higher than normal potential savings from doing the right repairs at the right times, the savings from improved assessments will be greater. MDT currently budgets about $10 million annually for deck rehabilitation of twenty to thirty structures. This budget is insufficient to keep up with the problem, as it would require forty years to rehabilitate 1000 bridges at 25 per year, and future rates of deck deterioration are expected to be higher than today, due to increasing traffic volumes and speeds. A 10% improvement in the life cycle cost of individual bridges due to more accurate assessment process would translate into an annual savings of $1 million.

Post-rehabilitation testing is needed, as it could reveal how well the different deck repair methods perform in Montana's geographic and climatic conditions. Such testing would help verify MDT pre- and post rehabilitation deterioration rates, since much of the published research on deterioration and rehabilitation effectiveness has been done in the more heavily populated coastal areas of the country, where deterioration rate factors are dissimilar to Montana's. Unlike coastal areas, Montana's climate is much higher, colder, and drier. In the winter, snowfall and freezing temperatures require the regular use of deicing salts on heavily traveled roadways. In addition to deicing with salt, Montana currently uses in excess of 1.8 million gallons of chloride-based liquid anti-icer on its roadways each year.

2.3 PROJECT METHODOLOGY

The project methodology changed during the course of the work. The initial plan was to locate all potential deck performance models and set up a rating matrix based on key MDT needs and objectives. With complex needs and too many vaguely described models, the original plan proved impractical, and it was therefore modified to simplify the rating process. The new plan was to divide MDT needs into two types, essential needs and rating needs. The essential MDT needs would be used to screen out most of the possible models, while those considered rating needs would be weighted for importance, and a rating matrix would be used to rate the models. This plan would reduce the complexity of the evaluation process. Again, difficulty was experienced in screening the models for conformance to essential needs, since most models consisted of nebulous mathematical ideas and concepts. The few that involved life cycle cost analysis were not suited for rehabilitation assessments. What MDT actually wanted was a system that used life cycle cost analysis in conjunction with an accurate life modeling process. So a third and final plan was conceived. The models and systems were reviewed for features and concepts that could be used to develop a system to meet the identified MDT needs. The goal was to see if it was feasible and cost-effective to develop such a system.

3.0 MDT NEEDS AND OBJECTIVES

The appropriate performance model and system must be able to satisfy various MDT needs and be compatible with their policies, as described in the following sections.

3.1 MANAGEMENT POLICIES AND PRACTICES

MDT is currently organized into one Bridge Bureau head office located in Helena, and five District offices located in Billings, Glendive, Butte, Missoula, and Great Falls. In general, district personnel participate with head office personnel in the decision whether to repair or replace a bridge or bridge component. Bridge Bureau personnel are ultimately responsible and are available to provide assistance when the work is extensive and cost studies are warranted. Major bridge repairs are usually planned to coincide with highway maintenance requirements. Highway maintenance work is programmed and scheduled by the local MDT district office, and the repair frequency is partially governed by the type of road. Sections of Interstate, for example, are repaired approximately every ten (10) to fifteen (15) years, and the bridges on a section would be assessed and scheduled for any necessary work at the same timing. By contrast, local road bridges are repaired on an as-required basis when deterioration reaches unacceptable levels.

3.2 INSPECTION AND TESTING POLICY

MDT carries out visual bridge inspections every two years under the National Bridge Inventory (NBI) system. Visual inspection data is entered and stored in the PONTIS bridge management system.

MDT does not use a regular or periodic deck-testing program. The Bridge Bureau does however carry out destructive and non-destructive deck testing when they deem it necessary. Bridges that are tested have generally been previously identified as candidates for rehabilitation by the districts, and the deck testing is used to establish the scope of work. The bureau uses the data collected from deck testing to design all required repairs. The designs are then forwarded to the districts for implementation. The data collected from deck testing is stored in a decentralized manner in paper files in the bridge bureau offices in Helena. No centralized database exists, nor is one being contemplated. MDT does not use the results of bridge deck testing to monitor the current condition, or predict the deterioration rate of bridge decks.

3.2.1 DECK DATA COLLECTED

Besides visual NBIS ratings, MDT collects the following bridge deck test data:

- Chloride Content: Field concrete powder samples are sent to a qualified laboratory for testing. Generally, samples are taken at three to five locations on the deck and at three different depths at each location. For spans longer than 30 m (100 ft), more locations are sampled. The test sample depths are: 6 – 19 mm (0.25 - 0.75”), 19 – 38 mm (0.75 – 1.5”), and 38 – 58 mm (1.5 – 2.25”).
- Half Cell Testing: Half-cell measurements are carried out in accordance with ASTM C-876 on a 1.5 m (5 ft) grid over the entire deck. The data is averaged and the numerical values are recorded on a plan drawing of the bridge deck, but no equipotential mapping is done. Sometimes a written description of the results is provided.
- Rebar Depth Measurements: Rebar depths are measured with a pachometer and recorded at every CSE test location. Depths are recorded on a drawing of the bridge deck, and mean, minimum, and maximum values are recorded, as well as the standard deviation.
- Mapping of Cracks, Delamination, Spalls, and Areas of Exposed Rebar: These are all mapped on the same plan view deck drawing. Delamination is located by sounding (ASTM D-4580), while cracks, spalls, and areas of exposed rebar are located visually. The total delaminated area is calculated. Crack widths are not measured, and crack lengths are not quantified. In order to effectively use crack mapping as a predictive tool, the widths and lengths, as well as the location of large cracks must be recorded. Locations of other tests, such as chloride tests and core samples, are also indicated on this drawing.
- Compressive Tests (ASTM C-39): Compressive tests are performed on 50 mm (2”) or 100 mm (4”) diameter cores taken from the deck. Generally one core is extracted for every 9.1 m (30 ft) of bridge length, or one for every span on shorter bridges.

Pull Off Tests: Pull-off tests are performed on 50 mm (2”) diameter concrete cores taken on polymer overlays. Four cores are tested at each location of interest. Usually only one or two locations are tested. Since thin polymer overlay is no longer a standard MDT rehabilitation method, pull-off tests are seldom performed.

3.3 DECK REHABILITATION POLICY

MDT determines potential rehabilitation options based on bridge deck condition as well as traffic volumes. Condition is assessed using the results from such tests as chloride content, copper sulfate electrode, cover depth, compressive strength, and delamination testing. MDT personnel from the Materials Bureau perform the tests. Visual inspections are conducted by District Staff on a regular cycle, and deck testing is coordinated to coincide with the development of new projects.

Depending on the long-term plans, current condition, and individual bridge needs and constraints, one of the following deck rehabilitation options would normally be selected:

- Do nothing;
- Replace bridge deck;
- Low slump or latex-modified concrete overlays;
- Temporary membrane and asphalt overlay;
- High molecular weight methyl methacrylate treatments (HMWM).

In addition, MDT is currently field-testing or assessing a number of other deck rehabilitation options including high performance and steel fiber reinforced concrete overlays, deep excavation overlays, Norcure Chloride Removal Process, Galvashield Anodes, and others.

3.4 MODEL FEATURES

This section reviews the necessary system (model) features, based on discussion with appropriate MDT staff. MDT does not currently store deck-testing data in electronic format, therefore the prospective model must be able to stand alone without relying on large amounts of historical data. Ideally, the model would be able to predict the future performance of the bridge based solely on the results of a single deck inspection. If MDT were to commit to a more routine deck inspection program, and develop a centralized database system for storing inspection data, more accurate models that rely on historical data to update model parameters could be investigated.

The input data required for the MDT model must be compatible with the test data currently collected during standard deck investigations. MDT has indicated that they may be open to collecting new types of data, such as corrosion rate for example, as long as the benefits were substantial and the additional costs were minimal. The preferred solution would involve only the types of data currently collected by MDT. Approximately 20 members of MDT's Bridge Bureau in Helena would use the proposed model for planning maintenance and rehabilitation activities.

Appropriate MDT staff provided input on the system features required to meet their minimum needs and objectives. They also rated the features in order of importance, and this information is summarized below.

ESSENTIAL FEATURES

The model must have the following features:

- Work from a desktop computer without the need of a centralized electronic database;
- Do accurate project level analysis of decks with chloride-induced deterioration;
- Be capable of purchase or development;
- Be capable of estimating repair costs on bridges of varying sizes and locations;
- Have been field-tested or validated for accuracy in a similar climate to Montana's;
- Predict the future performance of both non-rehabilitated and rehabilitated decks, including second or third generation repairs.

HIGH IMPORTANCE FEATURES

The following features are necessary, but some are subjective, as opposed to absolute features:

- Use life cycle cost analysis to recommend the optimum method for deck repairs;
- Predict the optimum timing for repairs;
- Be simple, intuitive, and user-friendly to operate;
- Be driven by the test data that MDT currently collects: CSE, chlorides, delamination, cover depth, compressive strength;
- Not require substantial increases in data collection costs;
- Predict the effects of various maintenance and rehabilitation activities.

MODERATE IMPORTANCE

The following features are desirable to lesser degree than those above:

- Low costs for new equipment;
- Low training costs;
- Predict all phases of deterioration;
- Work with black steel, epoxy coated rebar, galvanized rebar;
- Make predictions based on only one set of test data (or is historical data required?).

LOW IMPORTANCE

The following features were given low importance:

- Time before model can be used by MDT;
- Be commercially available.

4.0 DECK PERFORMANCE MODELS

For the purpose of clarity, definitions of some relevant terms are provided in Appendix A.

4.1 DECK DETERIORATION MECHANISM

Chloride ions are the cause of the MDT deck problems, and a description of the deterioration mechanism follows. In reinforced concrete the highly alkaline concrete creates a passive condition for the reinforcing steel in which corrosion does not occur. The light surface oxide on the reinforcing steel is highly stable in this environment. When chlorides have penetrated in sufficient quantity to level of the reinforcing steel, the passive steel condition is destroyed and corrosion begins. Chloride corrosion threshold is defined as the chloride concentration needed to initiate corrosion, but in reality the corrosion threshold is not constant. It varies with factors such as the actual concrete's properties of hydroxide ion concentration, moisture content, oxygen content, and others. The process of reinforcing steel corrosion in bridges has been the subject of thousands of technical and articles during the past forty years. The primary mechanism of reinforced concrete corrosion in North America involves chloride ions, which penetrate concrete and depassivate embedded steel to initiate the corrosion process, where expansive forces destroy the concrete cover, affecting structural integrity and riding safety. Corrosion is an electro-chemical process in which numerous corrosion cells appear on the rebar. Corrosion cells are like chemically powered batteries with the driving force resulting from the thermodynamic process of steel returning the iron to its natural oxidized state. A corrosion cell involves a complete electrical circuit with an anode or corroding portion and a cathode or protected portion. A partial current flow occurs through the steel connecting the anode and cathode, while the electrical circuit is completed by ionic flow through the moist concrete electrolyte. Corrosion cells are subdivided into macro-cells or micro-cells, depending on size. An example of a macro-cell would include the top reinforcing steel mat in a bridge deck as the anode, while the entire bottom reinforcing steel mat becomes the cathode. Deck macro-cells are created by differences in the deck profile. Chloride, moisture and oxygen contents in the top concrete surrounding the top rebar mat are higher than the concrete surrounding the bottom reinforcing steel mat. Micro-cells also result from the non-homogeneous nature of concrete, due to differences in oxygen, moisture, and chloride content resulting from cracks and such.

Balanced chemical reactions occur simultaneously at the anodes and cathodes, and electrical current flows between the two poles, through the reinforcing steel or the moist concrete.

Some of the oxidizing reactions that may occur at the anodes include:

$Fe^0 \rightarrow Fe^{++} + 2e^-$;

$Fe^{++} + 2Cl^- \rightarrow FeCl_2$;

$FeCl_2 + H_2O + OH^- \rightarrow Fe(OH)_2 + H^+ + + 2\ Cl^-$

$2\ Fe(OH)_2 + ½\ O^- \rightarrow Fe_2O_3 + 2\ H_2O$

Some chemical reduction reactions that may occur at the cathodes include:

$½\ O_2 + H_2O + 2e^- \rightarrow 2OH^-$

$2H^+ + 2e^- \rightarrow H^2$ (hydrogen gas evolution)

$O_2 + 4\ H^+ + 4\ e^- \rightarrow 2\ H_2O$ (acidic solutions)

$O_2 + 2\ H_2O + 4e^- \rightarrow 4\ OH^-$ (neutral solutions)

4.2 MODELING CHANGE IN DECK CONDITION

Performance models are mathematical expressions that can be used to predict deck deterioration, future condition and therefore, the optimum timing of expensive future bridge rehabilitation needs. Some other terms for performance model are service analysis engine, life prediction model or deterioration model. The models predict future condition as a function of 'last inspected' or 'last tested' condition, in conjunction with estimated deterioration rates that are related to individual bridge site factors. Project level, deck performance models are designed for specific deterioration mechanisms. MDT staff report that over 98% of all deck deterioration on their bridges is related to chloride-induced corrosion. This report will focus on findings related to chloride-based deterioration.

The process of change in deck condition from the beginning of chloride exposure to end of life is progressive and predictive, as demonstrated in Figure 4.1 Chloride-Based Deck Service Life Model (on the following page). Several stages occur sequentially, depending on whether the concrete is protected, badly cracked, and has black steel. The general stages involve chloride diffusion, corrosion initiation, initiation of concrete cracking at the rebar, and propagation of cracking to result in disintegration and spalling of the concrete surface. On bridge decks, the surface cannot tolerate high levels of damage without creating unsafe driving conditions.

Performance models can use the test data to more accurately identify the processes involved in the early onset of deterioration, from which future condition can be predicted if the relevant site parameters are known. The potential cost savings resulting from scheduling the proper repair methods at the optimum time are greatest for the sites exposed to the heaviest amount of chlorides and most aggressive exposure conditions, i.e. those with the potentially highest deterioration rates.

These site-specific deterioration rate factors may include deck rebar cover depth, salt application rates, local de-icing policies, geographic location, quality of construction, elevation above sea level, annual precipitation, annual snowfall, average daily traffic volume, speed limit, location over water or land, presence and type of deck protection systems, concrete age, quality and permeability, and maintenance/rehabilitation history.

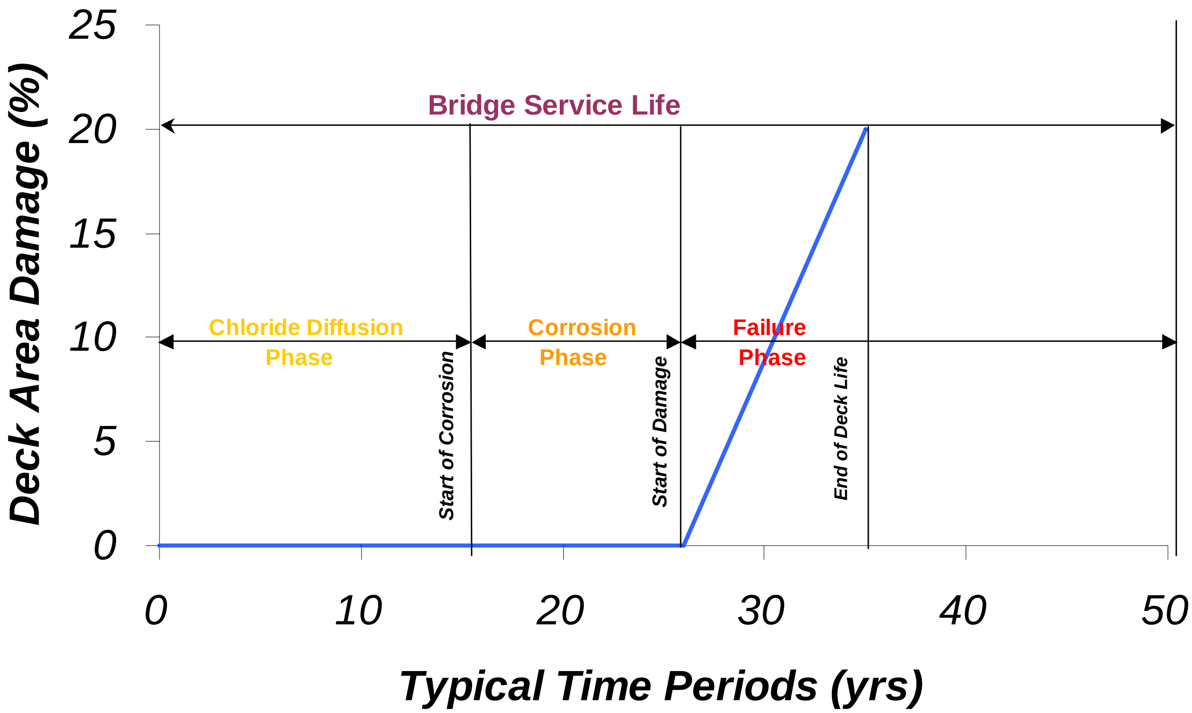

Figure 4.1 Chloride-Based Deck Service Life Model

In addition to evaluating the optimum time to repair, the model can be designed to recommend the type of repair (cathodic protection, chloride removal, high performance concrete overlay, etc.). Such a model will more often than not be restricted to one form of deterioration, such as corrosion-related distress. The model may or may not include cost analysis, although cost analysis is essential in establishing the optimum timing for repairs.

Some typical repair options to be evaluated by cost analysis within the model, would include (i) repair now, (ii) repair when deterioration has advanced to the unacceptable limit, (iii) repair at a more cost-effective or performance enhancing time in between these two scenarios, (iv) do nothing now and replace later.

4.3 EVOLUTION OF MODELS

Bridge deck performance models for chloride exposure have developed in many types, but they all have some common trends. Since models have evolved from the analysis of test data, the data itself has had significant influence on the models. Advances in computers have affected the growth and use of models. An example of recent advances is the use of probability in models, which is associated with the development of probability software programs. The need for probability analysis is based on the non-homogeneous nature of bridge decks, and the difficulty of modeling deck performance based on a small dataset. Model predictions for existing decks are made from some type of measurable deck condition data, in order to accurately identify the starting point, the time the test data was collected, from which to make future predictions. The test data being collected must be relevant, related to the failure mechanism the will eventually cause the end of deck life. One of the biggest obstacles to the development of accurate models has been the high number of site-specific variables related to individual bridge deterioration rates.

Many early performance models were based on visual data, often related to measuring the spalling, delamination and other forms of easily visible damage. Other early models have been based on visual ratings of components, sometimes involving overall condition indexes. The development of bridge inspection systems has increased the documentation of visual data, from which rates of deterioration and aging can be measured. The volume of inspection data collected in bridge management systems keeps increasing and represents a gold mine for future research.

Test methods keep improving over time and providing more data for use in deterioration models. Ground penetrating radar, pulse echo, infrared thermography and other new test methods are being improved and used more than ever before. Less expensive, more accurate test methods for chlorides and quantifying the extent of corrosion have been developed. This is resulting in adding to the pool of available test data for potential research purposes. Research into corrosion and the structural implications of concrete failure mechanisms keeps increasing, as the focus of university research has been changing from design and construction issues to system management issues in recent years. Deterioration mechanisms, repair materials and methods are some of the common research topics. Research attempts have been made to relate visual data, such as crack width and stains, with changes in structural capacity. New knowledge is becoming available for use in developing theoretical models. The development and use of life cycle cost analysis has also affected model evolution. Advancements in computer technology have assisted in the documentation process and the accessibility of cost information for future analysis and use in cost analysis.

Deck performance models require accurate input data to produce accurate output predictions. Early models were generally based on damage and visual data. Such models tended to fall into two types, theoretical models and damage models, neither of which had strong relationships to site-specific conditions, which create variety in the performance of different bridges. Models based on the rate of damage development are not as helpful as chloride diffusion models, since the former rely on data that occurs just prior to the end of service life. Damage models have less predictive ability than models based on chloride diffusion or corrosion test data. In addition, damage occurs at the end of service life, so the time period to intervene in the deterioration process may have already passed. As test methods and use have evolved, models have incorporated chloride and corrosion test data, in addition to visual. Newer models may include data on cracking, delamination, concrete permeability, concrete electrical resistance, cover depth surveys, chloride content profiles, half-cell and perhaps linear polarization surveys. Default values may be programmed into the process to be used when test data is incomplete.

4.4 LITERATURE SEARCH

ETI conducted a detailed literature review in an effort to identify existing deck performance models, or those under development, that may meet MDT's needs and objectives. The literature review identifies articles and papers on topics related to deck deterioration models, which are referenced in the text. Our process involved an extensive review of published materials available through Dialog's NTIS, Compendex and TRIS databases, and through several Internet searches. A comparative matrix (Appendix B) compares the features of the models on the basis of similar information.

Some goals of this literature review for each model were to identify:

- Project-level versus network-level functionality;
- Type of inspection and test data required;
- Output;
- Algorithm's used to determine the deck deterioration;
- Ability to predict the performance of existing and rehabilitated bridge decks;
- Whether the model is purely academic, or has been proven in the "real world".

Many models identified in this literature review are network-level deterioration models, used to predict changes in average condition ratings over time. Condition ratings are generally based on visual inspections, making them inadequate to plan timely protection or repair procedures for a concrete bridge subjected to salt-induced corrosion damage. It is also apparent that there has been no international consensus on prediction modeling. While there has been extensive research and development of deterioration models in Europe, and some development in North America, many jurisdictions have undertaken research based on their own specific requirements and independent of each other.

This literature review identified a significant number of bridge deck deterioration models, although only a few of them were found to partially or completely meet the specific needs and objectives of MDT. The three main general types of performance models for predicting the change in deck condition over time are regression models, Markov curves, and Bayesian models.

4.4.1 REGRESSION MODELS

Regression analysis is a type of data analysis that involves the estimation of the parameters of equations with observed data. In other words, it involves mathematically defining the best-fit curves that represent the observed condition data. These lines and curves, which model the deterioration of concrete elements over time, range from simplistic linear or curvilinear models to complex mathematical formulae with multiple independent variables. The accuracy of the model in predicting the future bridge performance is based solely on the accuracy of the data that was used to construct it. The curves and equations that make up this class of models are often based on historical data from a population of bridges, and generally represent the average response. If the population upon which the model is based is too broad, the model may not be useful at the project level. If the population upon which the model is based is too specific, its applicability may be limited to a very small number of bridges. One common type of regression curve model is the chloride diffusion model.

4.4.2 CHLORIDE DIFFUSION MODELS

Chloride diffusion models are based on calculating the time from initial chloride exposure at the surface to initiation of corrosion of the reinforcing steel, as well as the time it takes for corrosion-induced cracking to propagate from the steel to the surface of the concrete.

Fick’s Second Law is often used to describe the diffusion of chloride ions through concrete, and is expressed mathematically below. C is the chloride ion concentration at a distance x from the surface at t years and D is the apparent diffusion coefficient (Stewart and Rosowsky, 1998).

$$\frac{\delta C}{\delta t} = D\frac{\delta^2 C}{\delta x^2}$$

Crank's solution to Fick's Second Law is used to quantify the diffusion of chloride ions through a homogeneous medium. Crank's solution is shown below.

$$C(x,t) = C_o\left[1 - erf\left(\frac{x}{2\sqrt{tD}}\right)\right]$$

This equation relates the chloride content at a distance x from the concrete surface at time t if the other variables are known. C_o is the surface chloride content, D is the apparent diffusion coefficient and erf is an error function, a relationship that is not described by normal mathematical expressions.

Crank's solution is for the case of a constant surface chloride content and an infinite uniaxial diffusion space. Bridge decks do not typically meet these conditions. First, the chloride content in the top 13 mm (½ inch) of the deck is not constant, but varies seasonally, being the lowest in the fall and the highest in the spring. The chloride ion concentration at a depth of 13 mm (½ inch), however, increases as a function of the square root of time for the first four to six years, and then remains relatively constant. Assuming a constant surface chloride content will introduce an error in the service life estimate, but this error is small compared to the service life of the bridge. Secondly, the presence of the reinforcing steel contradicts the condition of an infinite diffusion space. The reinforcing steel will provide a barrier to diffusion, and will most likely cause an increase in the buildup of chloride ions at the bar locations. The best way to account for this discrepancy is to base the diffusion coefficients on measurements of chloride contents at varying depths directly over reinforcing bars.

A general limitation of chloride diffusion models is that they assume that the concrete is crack-free and homogeneous. The crack frequency in the concrete surface is an important consideration in assessing whether chloride diffusion calculations are relevant to a specific structure. The variables in the solution of the Fick's law are often assumed to be constants, although their values are known to vary with percent hydration, type and amount of supplementary cementitious material, percent consolidation, temperature, and percent saturation. For bridge deck ages greater than four years, temperature, percent saturation, and the amount and time duration of frozen pores appears to have the greatest influence on the diffusion coefficient at a given location. To account for these influences, the diffusion coefficient used in the model should be based on diffusion coefficients measured from a number of locations on an individual deck.

4.4.3 MARKOV CHAIN MODELS

Markov chains can be used to model the deterioration process if the conditions of facility elements are classified into discrete states, such as the NBI condition ratings of 0 to 9. They are widely used to predict changes in the condition index of a bridge or bridge elements. The condition index is generally based on visual inspection, and involves ranking the condition of a bridge or bridge element on a pre-defined scale. Markov chains are used to predict the rate at which the condition index will move from one ranking to another by identifying the percentage of a structure or element that will decline in a given time period. For example, assume that a structure can be rated as having a condition index of 3, 2, or 1, corresponding to good, average, or poor. A recent inspection found that 70 % of a structure was rated 3, 20 % was rated 2, and 10 % was rated 1. Historical precedent has shown that in any given year 40 % of a structure that is rated 3 will move to 2, and 25 % of a structure that is rated 2 will move to 1. These are known as transition percentages. Therefore, after 1 year, the condition index distribution will be 42 % - 3, 43 % - 2, 15 % - 1. The same transition percentages are applied to the new condition index distribution the next year to determine a new distribution for the third year, and so on. Generally, the transition percentages will be defined for different condition states, including structural types, exposure conditions, traffic volumes, or any number of other influential factors. Figure 4.2 shows another example of a Markov chain.

Markov chains do not account for the historical performance of a particular bridge. Performance predictions are based solely on the current condition of the bridge, and predicted average performance of all other similar bridges. Consequently, Markov chains often miss localized conditions that can drastically affect the deterioration characteristics of a bridge at the project level. For this reason, they have been traditionally limited to network level analyses, and for the most part do not meet the project level requirements set out by MDT.

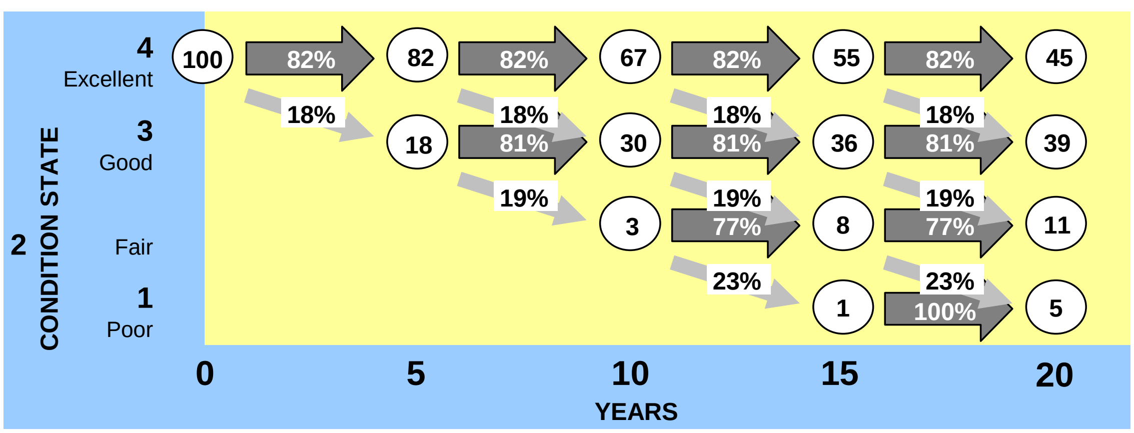

Figure 4.2 Example of a Markov Model

The two most popular bridge management systems in the United States, PONTIS and BRIDGIT, both use Markov processes to model the deterioration of their networks. Although they do not meet MDT's requirement of project level functionality, they are good examples of how Markov Chain models are implemented, as described in the next section.

4.4.4 BAYESIAN ESTIMATION

Bayesian estimation is a data analysis method that involves combining rational models with expert opinion. It allows the refining of the estimated probabilities of future condition states as new knowledge on specific sites is measured.

4.5 DOT USER SURVEY

Another possible source of information on deck performance models was other users. Potential users were identified as North American DOT personnel working in the area of bridge deck assessment.

4.5.1 GOALS

The primary goals of the user survey were to:

- Survey the state of the art of performance models from the user's perspective;
- Identify any existing models meeting MDT needs and objectives;
- Identify any models or systems being used by others in the bridge business;
- Get unbiased, independent opinions on the pros and cons of any prospective models or analysis tools in general.

Surveys often fail due to not reaching the specialists who have the desired information, so care was taken to ensure that these surveys reached the appropriate staff. The initial stages of the user survey consisted of developing a survey and mailing it electronically to approximately 35 state and provincial transportation authorities. The survey consists of thirteen questions and requires about ten minutes to be completed by an experienced bridge assessment engineer. The first question identifies whether or not the authority is currently using a bridge deck performance model. The second asks whether or not the user is aware of any other transportation authorities currently using a bridge deck performance model. The remaining 11 questions deal with the specifics of the model that the authority in question is using. If no model is being used, these questions are left unanswered.

A message accompanying the survey introduced Earth Tech and MDT, and briefly described the scope of this project. The message and survey were sent directly to Earth Tech contacts within each of the DOT's since each of these contacts is a potential model user. The message accompanying the survey instructed the contact to forward the survey on to someone else if they believed that that person was better qualified to complete it. A paper copy of the survey is included in Appendix C, along with a list of DOT's that responded (Appendix D).

4.5.2 FINDINGS

The user survey revealed that very few state transportation agencies are currently using a bridge performance model, and even fewer are using one at the project level. Of 35 DOT's only Louisiana, Ontario, Minnesota, Oregon, Indiana, and Connecticut indicated that they were actively using computer-based models to predict the deterioration of their bridges. Of those, only Louisiana, Ontario, and Oregon claimed to be using these models at the project level.

The Louisiana Department of Transportation has been using the ACI Life 365 model for approximately one year. This software program is described in a later section of this report. It is intended for design engineers to determine the most durable features for chloride-exposed, reinforced concrete elements. It uses chloride diffusion analysis to support cost analysis in decision-making involving the interaction of design features in varying exposure conditions. The program is currently used only for new construction, but it may be improved with additional features in future. Users of the program are pleased with its functionality and usability, and the department intends to continue using it for the foreseeable future.

Ontario Ministry of Transportation (MTO) has been developing a system, OBMS, since 1998. OBMS is designed as a project level system that predicts changes in the condition state of various bridge elements over time. The structural elements are visually rated on a scale of 1 (poor) to 4 (excellent). The system uses cost analysis to select the optimum repair method from a list of options.

5.0 INFORMATION FROM BRIDGE MANAGEMENT SYSTEMS

In contrast to performance models, bridge management systems (BMS), such as Pontis, involves the systematic collection, analysis and organization of data from a number of bridges for the purpose of optimizing the decision making process, regarding the management (maintenance, repair and replacement) of all the bridges in the system. They generally consider broader forms of degradation and problems (e.g. not just corrosion-related distress), such as functional obsolescence.

Bridge management systems (BMS) are generally intended for network level analysis of large bridge systems, where the accuracy of prediction is less important, due to being balanced by the large numbers of bridges involved. It is much easier to predict the deterioration rate of an entire bridge system than an individual deck. The network level functions of BMS systems are therefore different from the project level functions of deck performance models. A general deficiency of BMS systems is that they rely on visual inspection data and lack the type of detailed technical information needed to drive a performance model (Turner and Richardson, 1994). However, since BMS systems often contain a performance model subcomponent, a review of the main systems was included in the project literature search results that follow. BMS systems do not possess the following essential features needed by MDT:

- Do accurate project level analysis;
- Utilize existing MDT test data;
- Accurately predict deterioration rates in a similar climate to Montana's;
- Predict the future performance of both non-rehabilitated and rehabilitated decks, including second or third generation repairs;
- Accurately predict the optimum timing for repairs.

Our review of BMS systems will start with North American. Some systems that are not yet functional, such as Alberta Transportation's TIMMS, are not included in this report.

5.1 NORTH AMERICAN BRIDGE MANAGEMENT SYSTEMS

5.1.1 NORTH CAROLINA BMS

North Carolina was the first state to produce a system from BMS related research. Starting in 1982, individual components were developed in conjunction with North Carolina State University, and later synthesized into one BMS. The North Carolina BMS uses a linear deterioration model that continuously revises the deterioration rates based on historical data (Czepiel 1995). Input data for the model consists of NBI visual inspection ratings of a variety of bridge elements. A significantly larger number of elements are inspected in North Carolina than those required by the NBI.

NCDOT has invested extensive resources into cost modeling and budgetary forecasting. OPBRIDGE (Optimum Bridge Budget Forecasting and Allocation System) is the BMS component used for bridge management needs. OPBRIDGE includes element material deterioration rates, load-capacity deterioration rates, and average daily traffic growth rates (Khan, 2000). It determines the optimum repair strategy and optimum repair time for each individual bridge in a network. OPBRIDGE uses a bottom-up approach, similar in concept to OBMS, indicating that some degree of project level performance modeling is occurring.

5.1.2 PONTIS

The most commonly used BMS in the United States is PONTIS. PONTIS uses Markov chain processes to model deterioration of bridge elements, not just decks (Czepiel, 1995). The number of condition states, for which transition percentages (actions) and associated costs are defined, is limited to five per element (Thompson et al, 1998). Up to three actions including 'do-nothing' may be defined for each condition state of each element and the elements may be further classified in up to four categories of environments. This leads to a large number of transition matrices, which can be updated over time to reflect historical inspection trends. It is assumed that the condition states incorporate all of the information necessary to predict future deterioration.

The PONTIS BMS was designed to optimize budgets and programs for the maintenance and improvement of a states' inventory of bridges, and includes components such as: bridge inspection procedures, life cycle cost estimation, economic optimization, deterioration modeling, and software engineering (Khan, 2000). It can be used for new, old, and repaired decks. MDT currently owns PONTIS, and uses it to store visual inspection data. It is understood that MDT does not currently use any of the project level bridge assessment tools available from PONTIS.

5.1.3 BRIDGIT

BRIDGIT is another popular BMS that employs Markov chains to model deterioration. This system can predict the future condition states of unprotected and protected elements as well as protective systems (Hawk and Small, 1998). The future condition states predicted by BRIDGIT are independent of the element history, however, as with Pontis, historical information can be used to update the deterioration transition probabilities over time. The model accounts for effects of previous repairs on deterioration, effects of average daily traffic, and interplay between elements and protection systems. It can also be modified to suit the uniqueness of the bridge network by identifying its maintenance, rehabilitation, replacement, and functional improvement policies (Khan, 2000). The BRIDGIT BMS includes several modules that permit bridge agencies to store and modify inspection and maintenance information, create an unlimited number of inventory data items, and produce an optimization analysis of the network or any of its subsets. The BMS is a microcomputer based software package that allows viewing or editing information for each bridge element or protection system.

5.1.4 PENNSYLVANIA BMS

Another early BMS system is the Pennsylvania Department of Transportation (Penn DOT) System, which was implemented in 1986. In addition to storing and recording visual bridge inspection information, the BMS automatically generates project-level bridge improvement costs for maintenance, rehabilitation and replacement (Oravec, 1994). The system enables the user to predict future bridge needs by programmatically degrading the bridge condition and load carrying capacity over time, and it can also prioritize bridges for capital and maintenance improvements. The BMS analyzes the visual rating data using some supporting subsystems, which include:

- A Bridge Rehabilitation and Replacement Subsystem that provides cost estimating and prioritization of bridge improvement projects to support long range planning and programming decisions.
- A Bridge Maintenance Subsystem that provides cost estimating and prioritization of bridge maintenance activities for assistance in developing annual maintenance programs.
- A Modeling Subsystem that uses deterioration curves for bridge condition and load capacity to predict future bridge improvement budgetary requirements using different funding scenarios.
- An Automated Permit Rating and Routing Subsystem that provides decision support in the load rating, routing, and issuance of permits for overweight and oversize vehicles.
- A Report Subsystem that provides both standardized and customized report generation capabilities of any subset output data in the BMS.

The Bridge Rehabilitation and Replacement Subsystem prioritizes bridges for capital improvements based on the degree to which each bridge is deficient in meeting public needs.

The Bridge Maintenance Subsystem ranks individual bridges based on their required maintenance activities and estimates the costs of the maintenance. The prioritization procedure considers the effect of the most structurally critical maintenance activity need on the bridge and the bridge's individual impact on the overall system.

The Bridge Modeling Subsystem enables the user to develop future estimates for deficiency ratings, sufficiency ratings, condition ratings, load capacities, and improvement costs. Two basic deterioration models drive the Modeling Subsystem. These models allow for deterioration over time and establish new improvement codes that estimate future improvement costs for deteriorated bridges.

Penn Dot's system is a software package that runs on the State's mainframe computer. The system is undergoing constant improvements, including the use of computer pen pads in the field to ensure faster and more accurate data entry, data imaging, and photo and video storage capabilities. The program does not incorporate test data other than visual inspection ratings.

5.1.5 INDIANA BMS

The Indiana Department of Transportation (INDOT), through a Joint Highway Research Project at Purdue University, developed a project-level bridge management system (Khan, 2000). Based on a bottom-up approach, the project level analysis results are used at the network level to optimize the allocation of resources (Kleywegt and Sinha, 1994). The system uses visual inspection data.

The system has four core modules:

1. Decision tree (DTREE) analyzes condition and geometric data and uses Markov chains to model bridge performance over a five-year period. Assumptions and inputs for this module obtained from stored and input data include bridge location, year constructed, traffic volume, dimensions, type of structure, load rating, deck and superstructure condition rating, type of work proposed, and date of last inspection. The DTREE module analyzes this information in order to recommend an action for each bridge. There are 16 action levels, rating from deck rehabilitation to bridge replacement.
2. Economic Analysis (COST) uses recommended actions, costs, and action years from DTREE to perform life cycle cost analysis. The life-cycle analysis in the COST module uses the short term costs of the recommended action from DTREE and selects future actions and costs based on the present condition of the bridge and a predetermined long-term rehabilitation schedule. Based on the age of the bridge, recommendations may include no action, deck rehabilitation, deck replacement, or bridge replacement.
3. Ranking (RANK) ranks projects in order of need and perceived value to the community. The need for repair is based on the current inspection rating of the bridge. Algorithms are provided for quantifying the value of the recommended repair.
4. Optimization (OPT) uses the output from the RANK module and takes into account predefined budgetary and practical constraints to create a repair strategy that will provide the greatest increase in total value with the available funds.

The INDOT system uses IBM FORTRAN/2 and runs on an IBM compatible computer system. Planned enhancements to the program will incorporate safety and environmental factors (Woods, 1994).

5.1.6 OREGON DOT BMS

Oregon DOT has developed a series of deterioration curves to model the decline in the *Value Index* of a bridge (Sartain and Groff, 1999). The Value Index is defined as the current value of a bridge as a percentage of its replacement value. The current value of a bridge is determined from another module of the ODOT system, and is defined as the replacement value of a structure minus the cost of its needed repairs. When a bridge is new, it has a value index of 100. When it has aged to the point of replacement, its Value Index has declined to zero. The index is based on visual inspection data.

The deterioration curve profile depends on the structure's material type, climatic condition and design era (before or after 1975). Regression analysis was used to determine the unique deterioration profile of each of the 24 different classes of bridges defined in the ODOT system.

The results supported the use of second-order elliptical curves for timber and steel, third order ellipses for reinforced concrete, and fourth-order ellipses for prestressed concrete bridges.

With rehabilitation, the downward trend is interrupted and Value Index is restored in proportion to the value of the repair. Different rehabilitation strategies can therefore be compared, and life cycle cost analyses can be carried out in order to find the most cost effective way of maintaining a bridge at a certain Value Index level. Optimization modules perform similar analyses at the network level to determine the resources required to keep the entire bridge population at a given Value Index.

5.1.7 WESTERN CANADA MUNICIPALITIES BMS

Earth Tech Canada, in conjunction with six western Canadian cities, developed a Windows-based bridge management software system for inventories of less than 1000 bridges and bridge sized culverts (Kriviak, 1999). The system became functional in 1998 and is jointly owned by the seven development partners. Like many BMS systems, the system allows storage of descriptive inventory data, including construction drawings, photos, and reports linked to individual bridges. The system is primarily intended to manage the long-term network level budgets required to maintain the level of service, but it also has project level analysis features. At the network level the user can select various types of maintenance strategies for individual bridges to investigate their effect on the long-term system management costs. The basic strategies include ‘do nothing’, ‘reactive’, ‘proactive’, ‘proactive plus’, and ‘like new’. Network level ‘what if’ queries can be used to predict the most cost effective combination of maintenance strategies for the entire bridge network. The system uses a bilinear deterioration curve, based on visual ratings data, to model bridge deterioration. Influencer coefficients are used to modify the slopes of the deterioration curves on a site-by-site basis, and are automatically determined for each bridge based on site-specific parameters. The deterioration rate coefficients have default values for standard conditions, but they can be altered with new data over time or to represent different exposure conditions. Detailed life cycle cost analyses can be performed for individual sites based on user defined repair options, costs and predicted repair cycles.

Like many, this is an evolving system. The owning partner municipalities pay an annual fee for maintenance and upgrades of the system, which are made by Earth Tech. They may also contribute specialized improvements, which benefit the entire group. The system is not commercially available in the normal sense, as approval of the partner owners is needed for any new members to this group.

5.1.8 ONTARIO BRIDGE MANAGEMENT SYSTEM (OBMS)

One of the new BMS systems is OBMS. Ontario Ministry of Transportation (MTO) began development of this BMS in January 1998. It was intended to be a state-of-the-art system in terms of network functionality, and would also be highly detailed in its project-level performance model capabilities. At time of this report, the inventory and inspection data portions are in use by MTO, and the prediction model portion is being tested prior to start of use (Lai, 2002). The operating data is primarily from visual inspection ratings. The system uses network-level Markov chains that are modified by calculating project-level adjustment factors for project level analysis (Thompson et al, 1999). Elements are rated excellent, good, fair or poor. The Markov models are calibrated to reflect the history of the whole bridge population for the network level, but also involve project level adjustment factors, which alter the results of the global deterioration model, to reflect local characteristics at the project level. The project level model was developed from MTO expert opinion surveys to link the deterioration rates to site-specific factors, such as type of structure, drainage, and exposure conditions. Besides using visual ratings, the system can accept test data, which is converted to condition state ratings. These data include such things as type, severity and extent of deterioration, DART (deck assessment using radar technology) survey, chloride content, cracking, corrosion potential (CSE), cover depth, and delamination. The project-level analysis produces a list of project alternatives at varying funding levels, and selects one alternative for each program period to make up the optimal strategy for the bridge. The model performs a life cycle cost analysis for selecting and evaluating alternative options.

The model requires only two successive cycles of inspection before future predictions become possible, although greater numbers of successive inspections will improve the accuracy of the prediction. A network-level analysis takes new project-level data into account; a simulation-based system analyzes the entire inventory, or selected subset in one batch, updating all project-level and network-level results. The OBMS runs on WINTEL platform, Windows 95 with NT and Unix servers. It interacts with MTO's Integrated Highway Information System and Geographic Information System.

5.2 OTHER BRIDGE MANAGEMENT SYSTEMS

5.2.1 THE SWISS ROAD STRUCTURES MANAGEMENT SYSTEM

Ongoing efforts to develop a comprehensive road structures management system in Switzerland have resulted in a project called KUBA-MS (Ludescher and Hajdin, 1999). The system is based on the Pontis System, but KUBA-MS was conceived to overcome some insufficiencies of Pontis, especially at the project level. KUBA-MS deals not only with bridges, but also addresses deterioration of retaining walls, culverts and other concrete highway structures.

The Swiss Road Structures Management System incorporates Markov chains into its deterioration model. Each deterioration system-defined process has its own characteristic

Markov chain, which is updated by a statistical analysis of the condition data collected during routine inspections. Updating the Markov chains enables a self-learning process, which results in higher accuracy of the condition forecast at unique bridge locations. Exposure influence indicators are rated as favorable (slow deterioration, not directly exposed to weathering and not contaminated with chemically aggressive substances), average (moderate) or unfavorable (fast).

Optimization at the project level is based on a horizon of two to five years (short term planning). The strategic planning module addresses medium- and long-term planning at the network level.

5.2.2 FINNISH BMS

The Finnish BMS uses Markov chains to predict the effects of deterioration at the network level. The Finnish system has separate models for superstructures, substructures, riding surfaces, and bridge furnishings (Söderqvist, 1999). The model subdivides further into building materials, bridge-type and construction techniques. Altogether, there are 25 different categories of bridge items that can be classified into one of two environmental categories (salt vs. no salt).

This top-down system uses a deterministic approach to model the deterioration at a project level. The system models changes in a repair index (RI), determined by the inspector based on structural parts, class of damage, and repair urgency class. Deterioration curves, based on historical inspection data, opinion surveys, and expert evaluations are used to model changes in the repair index. A high RI score signifies serious damage. Data assumptions and inputs include:

- Damages and deterioration - exact location and extent;
- Effect of the damages on bearing capacity;
- Damage ratings (0 – no damage, 4 – serious damage);
- Repair urgency class;
- Inspector’s proposals for repair measures and their costs.

Condition of bridge structural elements is evaluated with respect to three types of damage groups, i.e. surface damage, structural damage, and water leakage.

The project level system uses results from the network level system to decide on repair measures required for individual repair projects. This is often referred to as a top-down model. An interactive computer program that includes life-cycle-cost analysis is used for planning and scheduling. Further development is required to improve the accuracy of the model predictions.

Finland’s Project Level Bridge Management System is programmed with Oracle Developer 2000 tools and runs in the Windows NT 4.0 environment.

5.2.3 JAPAN J-BMS

The Japanese J-BMS, which we believe is currently still under development, proposes to use multi-layered neutral networks to predict deterioration processes in existing bridges at the project-level (Miyamoto et al, 2000). The system aims to construct an optimal maintenance plan for repair or strengthening measures based on minimizing life cycle costs. J-BMS will use regression analysis curves to predict the change with time of load-carrying capability and durability of its structures. This system will use a reliability index, which they designate a mean soundness score, (100 – new bridge, 0 – can no longer remain in service). The index is intended to quantify load carrying capability and durability. Structures will be rated in several categories, which will include safe, fairly safe, moderate, slightly dangerous, or dangerous. The deterioration curves will represent change in the index over time and be depicted as integrated convex graphs. Load-carrying capability is defined as the bridge performance, based on the load-carrying capacity of the bridge member. Durability is defined as the ability of the bridge component to resist deterioration, which reflects the deterioration rate of the component.

This system sounds extremely complex, as it will involve consistently and uniformly rating a large number of items on a 0 to 100 scale for various components of the slab or girder. For the deck, the following items must be rated:

- Design;
- Execution;
- Road surface condition;
- Service condition;
- Deterioration of material;
- Cracking in haunch;
- Cracking in support zone;
- Midspan cracking;
- Overall damage;
- Load-carrying capability;
- Durability;
- Serviceability.

The Japan BMS will predict the deterioration process of existing bridge members, construct a maintenance plan for repair or strengthening based on minimizing maintenance costs and maximizing quality, and estimates the maintenance costs (Miyamoto et al, 2000). The program is being written in C programming language and will run on a personal computer.

5.2.4 HUNGARIAN BMS

In 1995, Hungary launched an adaptation of the American Pontis BMS. As part of the transition to Hungarian conditions, extensive changes to the Markov transition probability matrices had to be made (Gaspar and Lubloy, 1999). Using the expertise developed in transforming the network level analysis capabilities of PONTIS from American to Hungarian conditions, a project-oriented BMS was compiled in 1998. The project-oriented BMS modified the PONTIS network results with project-level bridge information, allowing project-type analyses. The concept employed in the project-oriented BMS is similar to the one employed in the Ontario system, OBMS.

5.2.5 BRIME (BRIDGE MANAGEMENT IN EUROPE) PROJECT

Another system that may still be under development is BRIME. Recognizing the large capital investment that Europe has in the road network, a research study was initiated in 1998 to develop a framework for a BMS in Europe. Funded by the European Commission under the Transport RTD program, the project was conducted by five partners (BAST, CEDEX, LCPC, NPRA and ZAG) under the coordination of Dr. Richard Woodward at the Transport Research Laboratory in the UK (Frohnsdorff, 1999).

The BRIME PL97-2220 Deliverable D13 Report (Woodward, 2002) describes a review of existing BMS and outlines the work undertaken to develop a frame for a BMS. In the report, Dr. Woodward notes that the study determined that the bridge management system must be modular and must incorporate the following modules:

- Bridge inventory;
- Knowledge of bridge and element condition and its variations with age;
- Evaluation of the risks incurred by users, including assessment of load carrying capacity;
- Management of operational restrictions and of the routing of exceptional convoys;
- Evaluation of the costs of the various maintenance strategies;
- Forecasting of the deterioration of condition and the costs of various maintenance strategies;
- Socio-economic importance of the bridge, including evaluation of the indirect costs;
- Optimization under budgetary constraints;
- Establishment of maintenance priorities;

- Budgetary monitoring on a short and long-term basis.

Within the framework, both project level and network level models are considered. Assumptions and inputs for the project level models include:

- Inspection observations, material testing, and inventory information;
- Condition state values for all elements and components of a bridge;
- Structural design calculations and as-built drawings;
- Inspection and test history for the bridge under investigation;
- Outputs from other models such as load carrying capacity, structurally vulnerable parts of the bridge and condition state-time trajectory for the vulnerable parts, as well as original input on the information from the assessment history of the bridge;
- Cause of deterioration;
- Maintenance work and traffic restrictions;
- Optimal maintenance method;
- Choice of maintenance strategies: replacement, strengthening, rehabilitation, repairs, preventative maintenance, and do nothing;
- Optimal maintenance program that predicts the timing and type of maintenance required, taking into consideration budget, network efficiency, and policy.

The Brime Report (Woodward, 2002) indicates how results from bridge management activities such as inspections, assessments, testing, maintenance, prioritization, and replacement can be combined to provide a framework for a computerized bridge management system at both the project level and the network level. Research does not indicate that actual software models have been developed.

6.0 LITERATURE FINDINGS ON DECK MODELS

The literature search also investigated papers on the topic of deck performance models.

6.1 HETEK

The Hetek model is a result of cooperation between the University of Gothenberg's Department of Materials, the Cementa Company in Sweden, and the AEC Laboratory and the Department of Mathematics of the Technical University of Denmark in Denmark. The model describes the process of chloride ingress and predicts the life of a black steel, unprotected structural component (Frohnsdorff, 1999) exposed to chlorides. The model data comes from testing and observations at the Traslovslage Marine Exposure Station in Sweden. Test data on concrete composition, rebar cover, environment (class of chloride), diffusion coefficients, and other factors was obtained with the Scandinavian NT Build 443 test method.

This chloride diffusion model is one of many that have been developed. It is intended for new structures and predicts the length of the diffusion period before the steel reinforcement begins to corrode. The chloride profile is characterized by surface chloride content, exposure time, background chloride content and diffusion coefficient of the concrete. It is noted that this model is not specifically for decks and was based on coastal conditions very different than Montana's.

6.2 VAL ET AL.

Val et al.'s (Stewart, 1999) described a reliability model for addressing the corrosion period of the service life curve for corroding structural elements. Only corrosion and not chloride diffusion is considered. Little definitive information was found on this model, and it is unknown what type of data it is based on, whether it can be applied to existing structures, and if it has been validated by real world test data as opposed to laboratory testing. Reportedly, the model focuses on the effects of the corrosion process; reduction in rebar area, loss of bond to concrete, and loss of structural capacity. The model uses a non-linear finite element program that considers collapse and deflection limit states. Immediate corrosion initiation is determined. Both homogeneous and localized corrosion propagation are reportedly modeled, and uniform corrosion rates are assumed.

6.3 FRANGOPOL ET AL.

This probabilistic structural reliability model (Frangopol et al., 2001) involves diffusion of chlorides, influence of design specifications on corrosion initiation, corrosion rates, flexural and shear limit states, and life cycle cost analysis. This is a conceptual model, rather than an existing system, and there is insufficient information to assess its strengths.

6.4 STEWART AND ROSOWSKY

This model calculates the probabilities of structural failure for a reinforced concrete continuous slab bridge subject to chloride-induced corrosion (Stewart and Rosowsky, 1998). Two independent sources of chlorides, application of de-icing salts and atmospheric marine exposure, are modeled probabilistically based on the behavior of corrosion initiation and propagation. Probabilistic cracking and critical threshold models are developed as well.

Assumptions and inputs required are:

- Initial bar diameter;
- Concrete cover;

- Chloride concentration.

Several aspects are not considered or need improvement in this model (Stewart and Rosowsky, 1998). They are: loss of bond, influence of mix design, environmental condition, workmanship on material behavior, bond cracking and delamination, punching shear serviceability, spatial variation, interaction between carbonation and chloride-induced corrosion, structural load and system modeling and practical implementation of time-dependent reliability analyses.

6.5 UNIVERSITY OF TORONTO

This University of Toronto, Windows-based software model was designed for addressing chloride ingress by diffusion, wicking, permeability, evaporation, convection and chloride binding (Frohnsdorff, 1999). The specific application was intended for reinforced concrete tunnel lining sections, rather than bridge decks, but the model contains many new relationships for modeling the movement of chlorides through concrete.

The large number of required types of data input include surface chloride concentration, diffusion coefficient and its change w/ time, activation energy of the diffusion process, initial chloride profile, permeation coefficient and its change w/ time, viscosity correction, binding coefficients, porosity, and temperature profile. However, the model provides default values for quantities for which actual data may not be available. The output data consists of the chloride concentration profile at any selected time interval. The model represents a substantial theoretical improvement on chloride movement through concrete, if somewhat impractical for use in real world bridge deck prediction.

6.6 ACI LIFE-365™

Due to concerns in the engineering community regarding the number of corrosion models being developed, the Strategic Development Council (SDC) of the American Concrete Institute (ACI) identified the need for a 'standard model' in May 1998. A workshop, "Models for Predicting Service Life and Life-Cycle Cost of Steel-Reinforced Concrete", was sponsored by the National Institute of Standards and Technology, ACI, and the American Society for Testing and Materials in Nov. 1998 (Frohnsdorff, 1999). An ACI SDC consortium was formed at that time to develop a consensus-based corrosion service life software tool. The consortium included: Master Builders Technologies, Grace Construction Products and the Silica Fume Association, among others. Members of ACI committee 365 were involved in the development as technical advisors.

The Life-365 model is a life cycle costing model for the design of new structures exposed to chlorides. The model can be used to compare alternative corrosion-design features using life cycle cost analysis for the purpose of improving durability. The model development was technically and economically supported by a group, which included individuals, private companies, and the American Concrete Institute 365 Service Life committee. This software program predicts the time to the onset of corrosion (initiation period) by diffusion analysis and the time for corrosion to reach an unacceptable level (propagation period) (Bentz and Thomas, 2001). The model accounts for the effects of design with chemical corrosion inhibitors, membranes, sealants, and epoxy coated bars. Temperature and driving chloride content profiles are defined for various situations in almost every major centre in North America, based on real world chloride data supplied by many local organizations. This is one of the few chloride diffusion models that evaluate the effect of temperature and the variation in driving chloride concentration on the diffusion rate of the chloride ions. This system also determines the repair schedule after first repair and estimates the life cycle costs based on the initial concrete costs and future repair costs. The model is unique in allowing the user to assess the performance of sealers, based on efficiency factors, which are based on testing. Some assumptions may be unrealistic. The user assumes the cost and extent of the first repair (i.e. percentage of area to be repaired) and the cost, extent and schedule of future repairs.

Model assumptions and inputs include:

- Geographic location;
- Type of structure and nature of exposure;
- Concrete cover depth;
- Details of each protection strategy scenario, such as water-cement ratio, type and quantity of mineral admixtures or corrosion inhibitors, type of rebar, presence of membranes or sealers;
- Surface chloride build-up rate;
- Sealer efficiency factor – chloride build-up from a cyclic-ponding exposure history – chloride content data obtained from a controlled comparative study;
- Chloride diffusion coefficient;
- Chloride threshold values.

Project-based Version 1.0 was released in October 2000 and Version 1.1 in December 2001. The model has many interesting features, but there is a limitation in that it basically assumes that the concrete structure will be crack-free. There are tentative plans to improve the model and also to upgrade it to include rehabilitation analysis in the future.

6.7 LOUNIS ET AL SERVICE LIFE PREDICTION

The National Research Council of Canada has proposed a research project based on a realistic modeling of the chloride ingress into concrete and the mechanisms of corrosion initiation and damage accumulation (Lounis et al, 2001). The National Research Council of Canada, along with private partners, is sponsoring the research project, and the model is expected to be ready in 2005. The project proposes to model variables that affect the deck performance as random variables. Service life would be modeled using reliability-based methods and Monte Carlo simulation will be used to produce an output distribution. A hydraulic-pressure analogy and a fracture mechanics approach (concrete cover is treated as a thick-wall cylinder subjected to the internal pressure build-up of expansive corrosion products) are taken. Assumptions and inputs for the model would include:

- Corrosion rate;
- Fracture properties of concrete;
- Cover-to-bar diameter ratio;
- Bar spacing;
- Degree of confinement provided by shear reinforcement;
- Level of traffic;
- Environmental load (e.g. thermal stresses);
- Rehabilitated and non-rehabilitated decks are considered.

Lounis et al also proposes to integrate the proposed service life prediction model with a life cycle costing model to develop a self-contained software package for bridge deck rehabilitation. The proposed software will enable the user to generate the density functions and cumulative distributions of the chloride profiles at different depths, determine time to corrosion initiation, cracking, delamination and spalling, and determine the service life of the bridge deck based on these times. It will operate at both a project and network level. If and when completed, this theoretical model may have some very interesting features.

6.8 VORSTER, BAFNA AND WEYERS

This economic-based deck model was designed for determining the optimum rehabilitation cycle for concrete bridge decks (Vorster et al, 1991). The model evolved from work performed under the Strategic Highway Research Program and on methodologies that were developed for quantifying the economic life of construction equipment. The creators modified the model to accommodate the special conditions found in bridge maintenance. The model is based on the assumption that patching and other deck maintenance operations result in future maintenance obligations. The model considers average conditions and deterioration rates, and does not assess the results of site-specific factors. It calculates the average annual cost of patching the deck for a number of years, then rehabilitating to extend life but not enhance original functional characteristics, so as to determine the optimum rehabilitation cycle.

The model is based on damage data such as area of deterioration from spalling, patches and chain drag, and estimated area to be rehabilitated. Unit cost ratios are included. Although this is an economic model, the time value of money and inflation have been omitted.

6.9 SHRP-S-377

The Strategic Highways Research Program Report SHRP-S-377 (1994) outlines the result of research conducted under SHRP Project C104 by Wilbur Smith Associates. In the report, a project level deterioration model is presented as part of a method for determining the most cost effective repair strategy for specific concrete bridge components. The model was a major early attempt to predict service of reinforcing concrete elements with chloride-induced corrosion.

The SHRP model uses deterioration curve nomographs to predict changes in the condition index of a structural concrete element over time. The *condition index* (S) can be calculated from three separate *indicator quantities* obtained from site inspections. The indicator quantities are:

1. Percent of bar-level chloride samples with chloride content higher than the corrosion threshold (CL).
2. Percent of concrete deck area that is delaminated (not including spalls) (DELAM).
3. Percent of concrete deck area that is spalled (SPALL).

To model the condition index, two points on the condition index vs. time curve must be known. When possible, these two points will define the age of the concrete at the initiation of deterioration (S = 1.9), and the age and condition index of the concrete at present. The condition index is calculated from the indicator quantities by the following formula.

$$S = CL + 2.5(DELAM) + 7.5(SPALL)$$

Once the two known points have been established, a curve, used to model future changes in the condition index, is fit through them. The curve is defined by the following relationship.

$$S(t) = 100 / [1 + A\exp(-Bt)]$$

The time (t) is in years. The unknown parameters A and B are found based on the two site-specific points already defined. These unknown parameters allow the formula to be tailored to each individual site based on actual site conditions. Each site will, therefore, have it's own unique deterioration curve.

If the concrete element in question is not yet showing any signs of deterioration, the method uses a modified Stratfull formula to predict the initiation of corrosion and damage. The Stratfull formula is based on empirical observations, and is not a chloride diffusion model, although it has been shown to be consistent with a diffusion approach. When the SHRP method was developed in the early 1990's, chloride diffusion analysis had not been widely accepted as a reliable means of predicting corrosion of steel in reinforced concrete.

The current rebar corrosion rate is required for modeling the effects of repair and rehab. The corrosion rate is used to predict the effects from proposed repairs, including the amount of service life extension gained from the repair. Using a similar process, the method can account for the effects of previous repairs on the deterioration curve of the structure. Based on corrosion model information, the method uses life cycle cost analysis to determine the most cost effective repair strategy and the optimal timing. The entire method can be done either by hand, with the aid of several charts and nomograph, or on a computer with the proprietary DOS-based software CORRODE. The software has not been updated to operate in a Windows environment. The SHRP-S-377 model is deterministic in nature. It assumes the corrosion threshold chloride concentration to be a constant, when in fact it has been shown to be a variable.

6.10 TTR (TIME TO REPAIR)

Fitch, Weyers, and Johnson (1995) developed a regression model from expert opinion data to predict the end of functional service life or amount of time remaining before a bridge deck must be repaired. The data was related to the amount of deck surface damage, mostly spalling, that would be tolerated prior to repairs. The model surveyed the opinions of snow-belt state department of transportation bridge engineers. The engineers were shown plan-view maps of existing bridge decks showing areas affected by cracks, delamination, spalls, and patches, and were asked to determine when each bridge should have been or should be rehabilitated. Sixty qualified opinions were received from engineers in 25 states that had previously been identified as using de-icing salts. A regression analysis of the survey results was carried out to form the model.

The model has only one independent variable, the percentage of worst traffic lane delaminated, spalled, and patched with asphalt (x), and one dependant variable, time to repair ($\hat{y}$). The best model developed had the following equation.

$$\hat{y} = -11.2 + 5.34x - 3.41x^{1.1}$$

Although the model cross-validated well with other samples of data within the project population, the coefficient of determination (R^2) of the above equation was only 22.0 %, i.e. 22 % of the variability observed within the survey responses can be described by the equation. This value suggests a poor consensus among the states' bridge deck decision makers and a low level of confidence in the model results. Because of the format of the survey, the applicability of the model is limited to typical two-lane bridge decks with total surface areas not greater than 2,800 m^2, on bare decks with normal reinforcing bars and does not consider probabilistic factors. The model predicts the life of overlays. This model is based on the average (mean) deck deterioration situation, and does not incorporate site-specific features related to the variation in bridge deck performance.

6.11 HOFFMAN AND WEYERS

Hoffman and Weyers (1996) developed a probabilistic time-dependent reliability model for bridge deck chloride diffusion due to de-icing salts. The model was reportedly based on extensive US data and is conservative in that it assumes failure occurs when corrosion is initiated. It also assumes uniform corrosion rates and ignores spatial effects and interaction of carbonation. This model was an early attempt to include probability in the prediction model, and it has evolved over time into the one described by Kirkpatrick in the following section.

6.12 KIRKPATRICK

Kirkpatrick's Virginia Tech Master of Science thesis (Kirkpatrick, 2001) was recently done under the guidance of Professor Richard Weyers. It shows how elements of uncertainty can be incorporated into a standard chloride diffusion model to more accurately predict the time to corrosion initiation. His model was validated using historical service life data from 129 Virginia bridge decks. The accuracy is limited, however, until the chloride threshold for corrosion initiation concentration is better defined. Service life predictions made with the probabilistic method presented here are shorter and closer to historical data than those made using the average value solution.

Kirkpatrick uses data collected from literature reviews to define probability distributions for each of the variables in Crank's solution to Fick's Second Law. An iterative process known as a Monte Carlo simulation is used to solve the problem. Discreet values for each variable are randomly sampled from the theoretical distributions provided. Crank's solution is then solved for the unknown variable. The entire process is repeated a sufficiently large number of times to accurately define a distribution for the unknown variable. The time from rebar corrosion initiation to visible deck damage is defined as a constant in Kirkpatrick's model, although current research is attempting to define this period for various newer types of reinforcement. This model assumes that the time of first repair occurs when 2.5 % of the worst span lane (the lane of travel showing the highest level of damage) of a bridge deck has deteriorated. Similarly, the model assumes that the end of functional service life is reached when 12% of the worst span lane of a bridge deck has deteriorated. Taking this into account, the 2.5^{th} and 12^{th} percentile of the unknown variable distribution (time in this case) is taken as the time to first repair and time to end of functional service life respectively.

Data input and assumptions include surface chloride concentration distribution, corrosion initiation concentration distribution, apparent diffusion coefficient distribution, cover depth distribution, and corrosion propagation time. This model was analyzed using S-Plus on a UNIX or PC platform, although any generalized risk analysis software could be used to perform the same analysis. The model has minor defects, such as a poor distribution factor for the initiation level of corrosion, but it represents the direction that diffusion models are currently evolving.

6.13 THOFT-CHRISTENSEN

Thoft-Christensen developed, in theory, a six-stage reliability based deterioration model for reinforced concrete elements. The six steps are: chloride penetration, corrosion initiation, corrosion evolution, initial cracking, crack evolution, and spalling. The first three steps use chloride diffusion modeling to determine the time to corrosion initiation, and the evolution of the corrosion of the reinforcement (Thoft-Christensen, 2002). Additional stochastic methods have been developed to model the final three steps.

The stochastic cracking model is based on previous research carried out by Liu and Weyers in 1998. By approximating the bridge deck as a thick walled cylinder surrounding a reinforcement bar, the amount of expansion due to corrosion required to crack the concrete can be estimated, and hence the time to cracking can be estimated.

The evolution of cracking is based on research conducted by Andrade, Alonso, and Molina in 1993, who developed a linear relationship between the amount of corrosion in a steel reinforcing bar and the width of cracking present at the surface of the concrete element. Based on this research, it should be possible to estimate the reliability of a structure based on the widths of the corrosion-induced cracks at the surface of the element.

Finite element modeling is proposed as a means to estimate the time for corrosion-based spalling of the concrete to occur. The report presents no finite element model, or method of creating one.

Assumptions and inputs consist of:

- Chloride ion concentration, as % weight of cement;
- Chloride diffusion coefficient;
- Concrete cover;
- Critical chloride concentration;
- Diameter of the reinforcement bar;
- Density of the corrosion products;

- Width of corrosion induced cracks.

The model assumes approximate distributions for each of the input variables (Weibull, LogNormal, or Normal), and uses Monte Carlo simulation to arrive at an output distribution of the reliability of the structure.

6.14 BMIS LABORATORY REGRESSION MODEL

The BMIS model was derived from analysis of a huge amount of visual data. The National Bridge Inventory Database (NBI) contains visual inspection data from over 600,000 bridges. Visual condition ratings (0 – failed, 9 – excellent) can be used to record bridge condition, and assuming that the ratings are done in a consistent fashion, where different inspectors give similar values, can be analyzed for change with time. Federal Highway Administration's (FHWA) BMIS Laboratory created an NBI-data-based regression model in 1995 that considers many prevalent environmental factors at the bridge level (Chase and Small, 1999). Due to the extreme size of this database, analysis potential has been improving with advances in computer technology. An essential feature of this model is that it involved the use of a geographic information system (GIS), which enabled a study of relationships between bridge deterioration and climatic conditions. Regression analyses were carried out to determine the influence of the following independent variables on change in the visual condition of deck, superstructure and substructure:

- Age;
- Average Daily Traffic;
- Frequency of Salting;
- Temperature Range;
- Freeze Thaw Cycle;
- Predominant Construction Material.

Three types of regression models were developed from the sample data: linear, non-linear non-parametric, and non-linear parametric. The linear model is generalized and is recommended due to its simplicity. The non-linear non-parametric model uses a general additive modeling procedure and smoothing operations to generate smooth plots. Since it is non-parametric, however, it is not readily usable for prediction. The non-linear parametric model is based on the non-linear non-parametric model and the generalized linear model. With the aid of a computer, the non-linear parametric model can also be made quite user friendly, and may provide a more accurate prediction of deterioration.

As with other visually based systems, the limitations of this model include regional inconsistencies in the inspection data and inability to basic inability of the visual ratings to quantify the electrochemical conditions occurring within the decks. The findings of this study are an important contribution to quantifying the effects of geographic location and climatic conditions on deck deterioration rates.

6.15 ALBERTA TRANSPORTATION CSE-BASED MODEL

This is a regression-type model based on analysis of corrosion test data on a core group of five hundred decks, tested on a five-year cycle over a twenty-five year period. During the early 1980's Alberta Transportation (AT) began developing a copper sulfate electrode (CSE)-based deck performance model (Kriviak et al, 1995). At first, the model was relatively accurate for only non-rehabilitated decks, but in 1993 a project on the performance of rehab overlays was completed and reported in Alberta Transportation Research and Development Report ATRB/RD/RR-94/01 "Service Life Prediction of Protective Systems for Concrete Bridge Decks in Alberta". The study used CSE and damage data to quantify the relationships between a number of site-specific deck deterioration factors and the service life of deck protection systems, such as concrete overlays and membrane/asphalt protection systems. Deck performance models were developed for the two primary failure mechanisms for concrete overlays, overlay-debonding and corrosion-induced delamination.

The model was further developed from 1998 to 2001 in several stages as part of the annual AT deck testing contract. Enhancements included incorporating two new significant service life factors: overlay quality (as reflected by crack frequency) and overlay timing (based on data analysis findings). Recent developments include the documentation of a rehabilitation database of repair history, costs, and before and after rehab CSE-based performance, from which further analysis can be done using the twenty-five years of test data. Alberta is just north of Montana and has a reasonably similar climate. A graphical example of the model of a rehabilitated deck is shown in Figure 6.1.

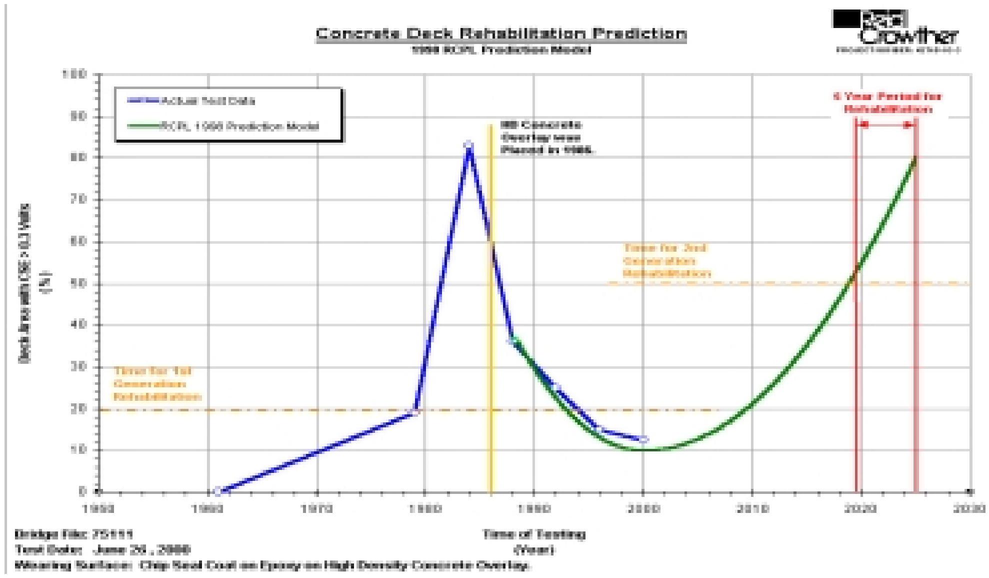

Figure 6.1 CSE Prediction Model

Montana's bare cast-in-place concrete decks are ideally suited for CSE testing. CSE testing is fast, non-destructive, and economical. The large amount of data obtained from each test allows for a probabilistic analysis of the results. MDT already includes CSE testing as part of their concrete deck evaluations, and has historical data that can be used to calibrate a new model.

Another advantage of the CSE-based model is that it has been validated on several hundred already repaired decks in similar climatic conditions as Montana.

6.16 GALVA PULSE-BASED MODEL

Advances in the field-testing equipment used for measuring deck corrosion create the possibility of this model. Linear polarization has long been used in laboratory testing for measuring corrosion rates, but development of a field test method has run into problems due to the slowness of the equipment and the non-homogeneous nature of decks, which requires that many readings be taken. The newest version of linear polarization test equipment is the Galvapulse, manufactured by Germann Instruments. The equipment consists of a small computer that collects and analyzes the electrical measurements of corrosion current, electrical resistivity, and voltage, which are generated by localized corrosion of rebar in concrete. Half cell and resistivity measurements are available almost instantaneously, while corrosion rate measurements generally take five to ten seconds. The major advantages of the product would relate to its accuracy and speed, which allows for collection of sufficient data to use statistically based data interpretation, such as mean and standard deviations of the three aspects of Ohm's Law.

The model that could be developed based on the Galvapulse instrument would likely be similar in form to the SHRP-S-377 model, but would use the test data from the Galva Pulse, and possibly other forms of test data such as delamination and spall surveys, to arrive at a condition index. The Galvapulse data would be used to identify the current corrosion condition of the deck. This data would be valuable in terms of its predictive ability on individual decks. Qualified, independent, international authorities are reportedly assessing the validity of the instrument, and it appears highly promising.

7.0 FEASIBILTY OF DEVELOPING A SYSTEM

The purpose of this section is to discuss the feasibility of designing a system, using state of the art performance model features and life cycle cost analysis to satisfy MDT's needs and objectives. The features are repeated below from section 3.4.

ESSENTIAL FEATURES

The model must have the following features:

- Work from a desktop computer without the need of a centralized electronic database;
- Do accurate project level analysis of decks with chloride-induced deterioration;
- Be capable of purchase or development;
- Be capable of estimating repair costs on bridges of varying sizes and locations;
- Have been field-tested or validated for accuracy in a similar climate to Montana's;
- Predict the future performance of both non-rehabilitated and rehabilitated decks, including second or third generation repairs.

HIGH IMPORTANCE FEATURES

The following features are necessary, but some are subjective, as opposed to absolute features:

- Use life cycle cost analysis to recommend the optimum method for deck repairs;
- Predict the optimum timing for repairs;
- Be simple, intuitive, and user-friendly to operate;
- Be driven by the test data that MDT currently collects: CSE, chlorides, delamination, cover depth, compressive strength;
- Not require substantial increases in data collection costs;
- Predict the effects of various maintenance and rehabilitation activities.

MODERATE IMPORTANCE

The following features are desirable to lesser degree than those above:

- Low costs for new equipment;
- Low training costs;
- Predict all phases of deterioration;
- Work with black steel, epoxy coated rebar, galvanized rebar;
- Make predictions based on only one set of test data (or is historical data required?).

LOW IMPORTANCE

The following features were given low importance:

- Development and implementation time;
- Be commercially available.

7.1 DISCUSSION

In the development of a conceptual system, choices will need to be made on the quality, accuracy, user-friendliness, and development costs of the system. The challenge will be to meet MDT's needs at least cost. The costs to be considered would include:

- development of the system;
- staff training needed to get the system operational; and
- operating costs to use the system.

Reducing costs in one of the above areas may result in higher costs in another. The benefits of the systems in terms of cost savings would also vary depending on the quality and type of system. Review of current information suggests that the system development costs could range from $150,000 to $400,000. The model could be developed in several formats with varying ranges in cost. At the low end, it could be done as a set of nomographs, and at the higher end as a software system. In addition, the quality of the system could vary substantially depending on the perceived needs for accuracy and user-friendliness.

Several possible options for a system to be developed might be:

- Minimum standard nomograph system;
- Minimum standard software version;
- Deluxe nomograph system;

- Deluxe software version.

7.1.1 BENEFITS OF SYSTEM

The potential benefits of the hypothetical system would be related to several items:

- cost savings from staff efficiency, less man-hours needed to perform current functions;
- cost savings from reducing the life cycle costs of bridges by performing the most effective repairs at the most appropriate times;
- ease of use;
- accuracy;
- the amount of use.

Some of these factors are interrelated. The savings would increase as the model was used more, which would be related to its user friendliness.

Based on cost analysis from a recent MDT job, the potential life cycle cost savings from using a deeper analysis with a wider range of rehabilitation options could range from about 15% to possibly 40%, depending on many factors, such as age and deck condition. A 10% improvement in life cycle costs might be a reasonable assumption. The annual MDT expenditures on bridge replacement and rehabilitation vary from year to year, from around $8 million up to about $13 million. Typical life cycle savings should average about $1M/year at current funding levels. Note that much of this amount is related to future savings due to increased performance. Annual savings on the initial bridge rehabilitation costs would likely be in the range of $100,000 to $200,000.

Another possible benefit of this system would be revenue generated by selling it to other states. Since no other state DOT was found to have a comparable system, there is a potential market for the product.

7.1.2 COMPARISON OF OPTIONS

The costs of possible system options would be:

- Baseline nomograph version – approx cost $60,000;
- Deluxe nomograph version – approx cost $100,000 to $150,000;
- Baseline software version – approx cost $160,000;
- Deluxe software version - $300,000 to $400,000.

The advantages of a software system would include:

- Simple documentation of all assumptions and calculations for filing and checking;
- Speed;
- Accuracy;
- Consistency of results from different staff.

The main advantages of a nomograph system would include be:

- Less of a black-box;
- More educational to use;
- Less expensive.

Disadvantages include:

- Requires greater skill and expertise to come up with correct answers;
- Life cycle cost analysis takes more time, maybe 6 man-hours per deck.

8.0 CONCLUSIONS

Based on our review of the state-of-the-art, we conclude there is no commercially available model that meets all of MDT's expressed needs and objectives. However, a reasonably accurate project level deck analysis tool with performance model and life cycle cost analysis, based on the use of deck condition data from existing MDT policies, could be developed to meet all of MDT's essential and high priority requirements, as well as most of the moderate ones. The current deck test data addresses all phases of the deck service life curve, and could be used to predict the optimum timing and optimum rehabilitation method for existing decks. It could also address issues related to the amount of concrete removal needed to optimize the cost-efficiency of the repair.

Approximate costs for such a model:

- A chloride, CSE, and damage based model for predicting condition change over time for Montana decks could be designed from existing information and currently existing information for a starting cost of $60,000;
- This model could be programmed for an additional cost of about $100,000;
- Alternatively, a deluxe model could be developed for up to $400,000.

9.0 RECOMMENDATIONS

Based on the cost/benefit analysis, we recommend that MDT consider the development of a system to meet the identified needs and objectives.

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APPENDIX A - DEFINITIONS OF SOME RELEVANT TERMS

Following are definitions of some terms used in this report.

Bayesian: a technique of combining inspection data and expert opinion (engineering judgment) in a rational manner to predict future conditions.

Black steel: uncoated, conventional reinforcing steel.

Bottom-up system: A bridge management system where the network level features are based on the project level analysis, therefore having accuracy that is related to that of the project level accuracy.

Bridge management system (BMS): a management system, usually computer-based, to store bridge inventory and condition data, and which is used to assist in the management of an entire bridge system. They usually contain performance models that are based on average deterioration rates for the entire system.

Chloride ion: a highly electro-negative ion, which when applied to concrete decks in the form of de-icing or anti-icing chemicals, can de-stabilize the normal passivity of reinforcing steel, initiating a process that destroys the functionality of the deck.

Chloride diffusion: the process by which chlorides move through the deck concrete to accumulate at the rebar until sufficient amounts cause rebar corrosion to initiate.

Corrosion: the electro-chemical process of reinforcing steel in concrete bridge decks, whereby the structurally important rebar reverts to its natural stage, where it has no appreciable strength, and in the process creates expansive forces in the concrete, resulting in riding surface spalling and potholes.

Copper sulfate electrode: a test method for measuring the probability and extent of deck corrosion. It measures the electrical characteristics of the chemical reactions occurring during corrosion, and when the data is taken correctly and analyzed statistically, it can be used to predict remaining deck service life.

Damage stage: the last stage of corrosion service life for a reinforced concrete element, in which visible corrosion damage has appeared; also known as propagation stage.

Deck Performance Model: The general definition of deck performance model would be a mathematical model or algorithm that can be used to predict the change of deck condition over time.

Deterministic: a process in which discrete solutions are reached, not incorporating probability.

Diffusion stage: the first stage of corrosion service life, where chloride ions are being transported to the level of the reinforcing steel until corrosion is initiated; also called the initiation stage.

Diffusion Coefficient: for this project, a parameter controlling the rate of chloride movement through concrete, related to climatic and concrete properties.

Life: service life (total time to replacement) of a chloride-exposed element, such as deck; the total time from construction until damage reaches the maximum tolerable level and functionality or structural capacity is compromised.

Life cycle cost: The long-term cost of a structure; a summary of present and discounted future costs resulting from a design or decision.

Linear polarization: for this project, a process of measuring the electrical current that is generated by rebar corrosion within the deck.

Markov Chain: a random process, used to predict the rate at which the deck condition index will move from one ranking to another by identifying the percentage of a structure or element that will probabilistically decline in a given time period.

Markov Process: a continuous random process in which the probability of occurrence of each random event in a series is dependent only on the immediately preceding event and independent of all historical events.

Monte Carlo simulation: a process in which introduces probability in the calculation such as a life prediction process, in which assumptions are used to assist random number generation in a high volume iterative process, which produces an output in the form of a probability distribution curve.

Network level: overall view of a bridge system; the 'big picture' analysis level.

Parametric: a variable in a mathematical expression, that when changed, yields another different but related mathematical expression from a limited series of such expressions.

Probabilistic: the inclusion of uncertainty into an equation or model, based on the concept that most events are less than 100% certain.

Project level: the analysis level where individual bridges, rather than the bridge system, are assessed or analyzed.

Regression analysis: a process for determining the statistical relationship between a random variable and one or more independent variables that is used to predict the value of the random variable.

Reliability: the probability of the success of a structure in performing its design functions.

Stochastic: another term for randomness or probabilistic.

Top-down system: a bridge management system, in which the project level analysis features are based on the network level analysis, resulting in their having less accuracy.

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Top-down system: a bridge management system, in which the project level analysis features are based on the network level analysis, resulting in their having less accuracy.

APPENDIX B - COMPARISON OF MODEL FEATURES

serving you with pride	Existing Model	Under Development	Proposed Model	Patented	Availability	Purchase Cost	Software Program	Mathematical Equation	Graphical Model	Network Level Analysis	Project Level Analysis	Design Model	Analysis Model (remaining Service Life)	Priorizes Repair	Predicts Optimum Time to Repair	Suggests Repair Method	Suitable for Epoxy Coated Rebar	Data Input Needed - Visual data	Data Input Needed - Test Data	Data Need - CSE	Data Needed - Chloride	Data Needed - Delam	Comments
Bafna and Weyers (23)	●							●			●							●					Virgina Polytechnic Institute, 200 Patten Hall, Blacksburg Virgina 24061-0105 Telpehone: 540-231-6635 Fax: 540-231-7532 Attention: Richard Weyers rweyers@vt.edu
BMIS Laboratory of FHWA (52)	●							●			●							●	●				Federal Highway Administration, 407, 7th Street S.W., Washington DC 20590 Telephone: 202-493-3038 Attention: Steve Chase
Bridgit (1,8,24)	●						●	●		●	●		●	●	●	●		●				●	American Association of State Highway Offices (AASHTO), 444 North Capitol Street N.W., Suite 249, Washington, DC 20001, Phone: (202) 624-5800 Fax: (202) 624-5806 E-Mail Address: info@aashto.org
Brime (Contecvet) (46,61)		●	●				●			●	●		●	●	●			●	●		●		Transportation Research Laboratory, Old Walkingham Road, Crowthorne, Berkshire, RG45 6AU UK Telephone: 44 (0) 1344 770007 Fax: 44 (0) 1344 770880 Attention: Dr. Richard Woodward
Cady and Weyers (35, 38,62)			●					●		●	●		●		●			●	●				Virgina Polytechnic Institute, 200 Patten Hall, Blacksburg Virgina 24061-0105 Telpehone: 540-231-6635 Fax: 540-231-7532 Attention: Richard Weyers rweyers@vt.edu
Earth Tech BMS (9)	●	●		●			●	●	●	●	●		●					●					Earth Tech, 17203 103 Avenue, Edmonton Alberta T5S 1J4 Telephone: 780-488-6800 Fax: 780-488-2121 Attention: Gary Kriviak
Earth Tech -other models	●						●	●	●		●		●		●			●	●	●	●		Earth Tech, 17203 103 Avenue, Edmonton Alberta T5S 1J4 Telephone: 780-488-6800 Fax: 780-488-2121 Attention: Don Hamilton
Finnish BMS (14,41, 59, 60)	●						●			●	●		●	●	●	●		●	●		●		Finnish Road Administration, Traffic & Road Research, PO Box 33, Fin 00521 Helsinki Tel: +358 20 422 2632 Fax: +358 20 422 2236 Attention: Marja-Kaarin Soderqvist marja-kaarina.soderqvist@tiehallinfo.fi
Heteck (46)	●							●	●		●		●					●			●		AEC A/S Sortemosevej 2 DK-3450 Allerod Denmark. Tel: +45 66 10 Local 15 Fax: +45 45 66 14 66 Attention: Jens M. Fredericksen jmf@aec_dk.com
Hungarian (PONTIS-H) (28)	●						●			●	●				●			●					Institute for Transportation Sciences, Budapest Hungary: Közlekedéstudományi Intézet Rt., Budapest, Thán Károly utca 3-5., Postal code: H-1119 Phone: (+36 1) 205-59-36, Fax: (+36 1) 206-57-05, Attention: Laszlo Gaspar and Laszlo Lubloy e-mail: h1817gab@helka.iif.hu
Indiana BMS (1,33)	●						●			●	●		●		●	●		●			●	●	American Concrete Institute, PO Box 9094, Farmington Hills, MI 48333 Telephone: (248) 848-3700
Japan BMS (J-BMS) (16)		●	●				●		●		●		●		●	●		●					Yamiguchi University, Department of Computer and Systems Engineering, Ube 755-8611 Japan. Attention: A. Miyamoto and H. Nakamura
Kirpatrick (38)			●				●				●			●							●		Trevor Joe Kirpatrick, Master of Science Thesis, Virgina Polytechnic Institute and State University, Blacksburg Virgina. July 2001
Lounis Service Life Pred (26)			●	●	2005		●			●	●		●	●	●						●	●	Institute of Research in Construction, National Research Council of Canada, 1200 Montreal Road, Ottawa ON R1A 0R6 Phone: 613-993-5412 Fax: 613-952-8012. Attention: Zoubir Lounis zoubir.lounis@nrc.ca
North Carolina -Opbridge (1,3)	●	●					●			●	●			●	●	●							Phone: (+36 1) 205-59-36
OBMS (25)	●						●				●	●	●	●	●	●	●	●	●		●	●	Institute for Transport Sciences
Pennsylvania DOT (1)	●						●			●	●		●	●	●	●		●					Pennsylvania Department of Transportation, Keystone Building, 400 North Street, Harrisburg PA 17120 Telephone: 717-787-2838 Fax: 717-787-1738 Attention: Mr. Jonathan Oravec
SHRP-S-377	●			●			●		●		●		●			●					●	●	Transportation Research Board, National Academy of Sciences, 2001 Wisconsin Avenue N.W., Washington D.C. 20007 Tel. (202) 334-2934 Fax: (202) 334-2003
Swiss Federal Institute KUBA-MS (12, 49)	●		●				●	●		●	●		●	●	●	●		●	●		●	●	Swiss Federal Institute of Technology, ETH Zentrum, C4-8092 Zurich, Switzerland. Phone: +41 (0) 1/632 11 11 Fax: +41 (0) 1/632 10 77
UK Highways (45, 64)			●						●	●	●		●	●									Highways Agency, London UK. Tel: 08457 50 40 30 Attention: Parag C. Das ha_info@highways.gsi.gov.uk
Enright & Frangopol, Bayesian Estimation (17)	●						●	●	●	●											●		University of Colorado, Department of Civil Engineering, Environmental and Architectural Engineering, Campus Box 428, Boulder CO 80309-0428 Telephone: 303-492-7165 Fax: 303-492-7317 Attention: Professor Dan M. Frangopol dan.frangopol@colorado.edu
Frangpool (19, 54)			●					●	●	●					●			●			●		University of Colorado, Department of Civil Engineering, Environmental and Architectural Engineering, Campus Box 428, Boulder CO 80309-0428 Telephone: 303-492-7165 Fax: 303-492-7317 Attention: Professor Dan M. Frangopol dan.frangopol@colorado.edu
Hoffman and Weyers (54)	●																						Virgina Polytechnic Institute, 200 Patten Hall, Blacksburg Virgina 24061-0105 Telephone: 540-231-6635 Fax: 540-231-7532 Attention: Richard Weyers rweyers@vt.edu
Life-365 (39)	●			●	●		●					●						●					Indian Department of Transportation, 100 N. Senate Ave., Indianaoplis, In 46204 Attention: Robert Woods (317) 232-5165
Mori ad Ellingwood (21)													●								●		Professor Y. Mori ymori@mail.cc.tohoku.ac.jp
Oregon DOT BMS (30)	●						●		●	●			●		●	●		●					Oregon Department of Transportation, 355 Capitol St. NE, Salem OR 97301-3871 Telephone: (503) 986-3396 Attention: Martha Sartain, Bridge Management Systems Manager
Pontis (1,3,4)	●						●			●		●	●		●	●		●					American Association of State Highway Offices (AASHTO), 444 North Capitol Street N.W., Suite 249, Washington, DC 20001, Phone: (202) 624-5800 Fax: (202) 624-5806 E-Mail Address: info@aashto.org
Rilem (46)			●		●							●	●										RILEM, ENS - Batiment Cournot, 61 Ave du President Wilson, F-94235 Cachan Cedex France.Tel: 33 1 47 40 01 13 Fax: 33 1 47 40 01 13 www.rilem.org
Stewart and Rosowsky (54)		●								●		●						●					University of Newcastle, Department of Civil, Surveying, and Environmental Engineering, Newcastle NSW, Australia. Attention: Mark G. Stewart
Thoft-Christensen (54,57)			●					●	●	●			●		●			●	●		●	●	Aalborg University, Dept of Buildings, Technology and Structural Engineering, Sohngaardsholmsvej 57 DK-9000, Aalborg Denmark. Telephone: +45 9635 8580 Fax: +45 9814 8243 Attention: Dr. Palle Thoft-Christensen, Professor. ptc@civil.auc.dk
Time to Repair (TTR) (18)			●							●			●	●				●				●	Virgina Polytechnic Institute, 200 Patten Hall, Blacksburg Virgina 24061-0105 Telephone: 540-231-6635 Fax: 540-231-7532 Attention: Richard Weyers rweyers@vt.edu
University of Toronto (46)	●						●			●											●		University of Toronto, Toronto, Ontario M5S 1A1
Val et al (54)										●													Technion, Isreal Institute of Technology, Borowitz Bldg. , Rm. 519, Haifa 32000, Israel Tel: +972-4-8292276 Fax: +972-4-8323433 Dimitri Val E-mail: val@tx.technion.ac.il

Bridge Deterioration Model User Survey

E A R T H T E C H

Contact Information

Organization:

Contact Name:

Contact Phone Number:

Contact Email:

Address:

1. Does your organization currently use a computer-based model to predict the future performance or deterioration of your bridges? In this case, the term 'model' means a deck life prediction model based on chloride induced corrosion that is used to determine what type of repairs are needed, and when the repairs should be carried out.
   - ☐ YES ☐ NO

2. Are you aware of any other DOT's currently using a deck life prediction model?
   - ☐ YES ☐ NO

   If YES, which ones?

If you answered YES to question 1, please answer the following questions. Otherwise, please save this questionnaire and return it to the sender.

3. Is the model you use commercially available?
   - ☐ YES ☐ NO

   If YES, what is the trade name under which it is sold?
   - ☐ Pontis BMS
   - ☐ Bridgit BMS
   - ☐ Life 365
   - ☐ Other (Please Identify)

4. Is the model you use part of a larger bridge management system?
   - ☐ YES ☐ NO

   If YES, which one?

5. Under which of the following categories would you classify the deterioration model you are currently using?
   - ☐ Markovian Chain
   - ☐ Chloride Diffusion Model
   - ☐ Deterioration Curve / Regression Model
   - ☐ Other (Please Describe)

APPENDIX C - USER SURVEY FORM

6. List all of the inputs required by the model.	
7. List all of the outputs available from the model.	
8. Is your model most useful for predicting the future performance of an individual bridge, or the average future performance of a population of bridges?	☐ Individual ☐ Population of Bridges
9. How long have you been using the model?	☐ Years
10. In your opinion, what are the good features of the model?	
11. In your opinion, what are the bad features of the model?	
12. If you could make any improvements to the useability and/or performance of the model, what would they be?	
13. On a scale of 1 to 5, how would you rate the user-friendliness of the model? (1 = Not User Friendly, 5 = Very User Friendly)	☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

Question		1	2		3		4		5	6
Contact Information		Does your organization currently use a computer based model to predict the future performance or deterioration of your bridges?	Are you aware of any other DOT's currently using a deck life prediction model?	If YES, which ones?	Is the model you use commercially available?	If YES, what is the trade name under which it is sold?	Is the model you use part of a larger bridge management system?	If YES, which one?	Under what category would you classify the model you are currently using?	List all of the inputs required by the model.
Organization	Alaska DOT	NO	NO							
Name	John Orbistondo									
Phone Number	907-465-8941									
Email	john_orbistondo@dot.state.ak.us									
Mailing Address	3132 Channel Drive, Juneau, AK 99801									
Organization	Indiana DOT	NO	NO							
Name	George Snyder									
Phone Number	317-232-5163									
Email	gsnyder@indot.state.in.us									
Mailing Address										
Organization	Missouri DOT	NO	NO		NO	Federal SHRP Program had a Life Cycle Cost Method - but it was written in DOS and no money has ever been set aside to upgrade it.	NO		Federal SHRP Program had a Life Cycle Cost Method - but it was written in DOS and no money has ever been set aside to update it.	ADT on bridges
Name	John Wenzlick									Chloride application
Phone Number	573-751-1039									chloride content of cores
Email	wenzlj@mail.modot.state.mo.us									
Mailing Address	1511Missouri Blvd., P.O. Box 270, Jefferson City, MO									
Organization	West Virginia Division of Highways - MCS&T	NO	NO							
Name	Christopher Preston									
Phone Number	(304) 558-3030									
Email	Cpreston@dot.state.wv.us									
Mailing Address	190 Dry Branch Road; Charleston, WV 25306									
Organization	Transportation Resear	YES	NO		YES	LIFE 365	NO		CHLORIDE DIFFUSION	see LIFE 365
Name	John Eggers									
Phone Number	225-767-9103									
Email	jeggers@dotd.state.la.us									
Mailing Address	4101 FGourrier Ave. Baton Rouge, LA 70808									

Question		7	8	9	10	11	12	13
Contact Information		List all of the outputs required by the model	Is your model primarily used at the network level or the project level?	How long have you been using your model?	In your opinion, what are the good features of the model?	In your opinion, what are the bad features of the model?	If you could make any improvements to the useability and/or performance of the model, what would they be?	On a scale of 1 to 5, how would you rate the user-friendliness of the model? (1 = Not User Friendly, 5 = Very User Friendly)
Organization	Alaska DOT							
Name	John Orbistondo							
Phone Number	907-465-8941							
Email	john_orbistondo@dot.state.ak.us							
Mailing Address	3132 Channel Drive, Juneau, AK 99801							
Organization	Indiana DOT							
Name	George Snyder							
Phone Number	317-232-5163							
Email	gsnyder@indot.state.in.us							
Mailing Address								
Organization	Missouri DOT	Economic analysis of different repair strategies.	NETWORK LEVEL		At least SHRP program (CORRODE) could figure a life cycle costs with a few inputs	Program was in DOS and not supported at all.	This program in a Windows type version would be a starting place for analyzing bridges but the conversion to Windows was never funded by FHWA or AASHTO.	2
Name	John Wenzlick	Life cycle cost analysis of a single bridge to one treatment						
Phone Number	573-751-1039							
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Mailing Address	1511Missouri Blvd., P.O. Box 270, Jefferson City, MO							
Organization	West Virginia Division of Highways - MCS&T							
Name	Christopher Preston							
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Organization	Transportation Resear	see LIFE 365	NETWORK LEVEL	1	It allows the design engineers to have a better estimate of time till corrosion is initiated. As opposed to taking a SWAG!	Like most new programs, it could, and I'm sure will, beocme more versatile with upgrades.		3
Name	John Eggers							
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