DETERMINATION OF THE END OF FUNCTIONAL SERVICE LIFE
FOR CONCRETE BRIDGE COMPONENTS

by

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(Abstract)

The transportation engineering community of the United States faces a tremendous problem: the gradual deterioration of the nation's bridges. A major component of the overall bridge deterioration problem is the corrosion-induced deterioration of reinforced concrete bridge components that are exposed to de-icing salts. The progression of events resulting from corrosion of the reinforcing steel includes cracking, delamination, spalling, and patching of the surface concrete.

Bridge components reach the end of their functional service life when the level of damage warrants rehabilitation. The objective of this study was to determine the end of functional service life for concrete bridge decks, piers, and abutments by quantifying terminal levels of physical damage. The approach for quantifying terminal damage levels involved obtaining recommendations from state Department of Transportation (DOT) bridge
engineers via an opinion survey.

A field study of 18 existing concrete bridges that had been designated for rehabilitation was conducted to develop concrete bridge component maps showing areas of physical damage. Deck damage maps were produced using a ground-based photogrammetry system developed in this study, while pier and abutment damage maps were drawn by hand in the field. Survey Kits based on the component damage maps were distributed to bridge engineers in 25 states that use de-icing salts. The engineers evaluated the maps and recommended when each component should be, or should have been, rehabilitated. Based on the engineers' responses, linear regression prediction models were developed to relate the recommended bridge component rehabilitation time point to the physical damage level. Based on the prediction models, two viable terminal damage levels for concrete bridge decks, and a partial terminal damage level for concrete bridge piers, were quantified.
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This thesis is dedicated with love and gratitude to the author's parents, Gary and Madeline; to his brothers, David and Bryan; and to Margo.
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1.1 DESCRIPTION OF THE PROBLEM

The transportation engineering community of the United States faces a tremendous problem: the gradual deterioration of the nation's bridges. The problem is critical because bridges are one of the most important components of our transportation infrastructure. First, the nation's 575,675 bridges [1:184] represent a large capital investment by the public. Second, bridges provide time and money savings to the travelling public by enabling traffic to rapidly traverse traffic flow impediments, such as valleys, waterways, and other roads. Remedial bridge work can be costly not only in terms of labor and materials, but also because of the public cost of increased travel time resulting from detours or restricted traffic flow. Thus, keeping bridges open and functioning at an acceptable level of service is necessary to maintain an efficient transportation system.

A major component of the overall bridge deterioration problem is corrosion-induced deterioration of reinforced concrete bridge components. Chloride-laden seawater and water containing dissolved chloride de-icing salts can penetrate the concrete cover layer, allowing chloride ions to initiate corrosion of the steel reinforcing bars. The
resultant expansive corrosion products crack the concrete surrounding the reinforcing steel. Spalling (loss of cover concrete) occurs when the cracks intersect the concrete surface, allowing pieces of the cover concrete to fall out or be knocked out by traffic loads. Delamination of the cover concrete occurs when cracks between adjacent reinforcing bars intersect.

The progression of events resulting from corrosion of reinforcing steel includes cracking, delamination, spalling, and patching of the surface concrete. As physical damage accumulates, the riding surface of the deck and the aesthetic appearance of the entire structure become impaired, reducing the functional service life of the bridge. If allowed to continue for many years, corrosion of reinforcing steel can threaten the structural strength of the bridge.

The scope of the corrosion-induced deterioration problem is broad, since 25 states in the contiguous U.S. use de-icing salts each winter to remove ice from roads and bridges [2:36,3]. According to the National Bridge Inventory, there were a total of 131,550 cast-in-place concrete bridge decks in these 25 states as of 1991 [4]. Each one of these decks is susceptible to corrosion-induced damage. Manning stated in 1986 that "the unfunded
liability to correct corrosion-induced distress in bridges is approximately $20 billion and the figure is increasing at almost $500 million annually" [5:TRA 4-2].

In 1984, Cady and Weyers proposed a corrosion-deterioration model for concrete bridges [6:35,7,8:331]; see Figure 1. The model presents a qualitative relationship between "Cumulative Percentage of Concrete Surface Area Damaged" and "Time", and is believed to be applicable to any reinforced concrete bridge component exposed to chloride salt solutions. The model is defined by four critical points on the Time axis:

1. Time at which chloride ion diffusion through the cover concrete begins.
2. Time at which corrosion of the reinforcing steel begins.
3. Time at which cracking of the concrete surrounding the reinforcing steel begins.
4. Time at which the bridge component reaches the end of functional service life due to an accumulation of physical damage.

Each of the four time points corresponds to a level of physical damage.

By 1990, the year this study was undertaken, the diffusion, corrosion, and damage accumulation time periods
Figure 1. Corrosion-deterioration model for concrete bridges. After Cady and Weyers [6:35,7:8:331].
of the model had been studied and estimated [6,8]. However, the time point and damage level defining the end of functional service life had not been determined conclusively. The end of functional service life is that time point in the life of a bridge component when the level of physical surface damage warrants rehabilitation of the component. For concrete bridge decks, rehabilitation is defined as patching of deteriorated areas and overlaying the deck with a new riding surface. For concrete bridge substructure components, rehabilitation is defined as patching or encasement. Unlike the other three time points, the end of functional service life is determined by bridge engineers, who make decisions regarding the time to rehabilitate a concrete bridge component. The end of functional service life is distinctly different from the end of structural service life, the time point at which the bridge damage level warrants demolition of the structure.

As of 1990, there was no consensus within the bridge engineering community regarding the level of physical damage that justifies rehabilitation. Decisions about rehabilitation were made by individuals or small groups within each state. The physical condition of bridges recommended for rehabilitation varied considerably from
one locality to another.

The lack of a quantitative definition for the end of functional service life is a problem for two reasons. First, it prevents any objective means of prioritizing bridge rehabilitation needs within each state and nationwide. Second, it hinders engineers' ability to evaluate bridge treatments based on life cycle cost. The service life of a bridge component cannot be determined unless the end of service life is defined.

The engineering economical consequence of not having well-defined endpoints of functional service life for concrete bridge components has been recognized by the transportation engineering community. The 1991 report of the Secretary of Transportation to the United States Congress stated the following [2:23]:

Since the earliest days of highway development, officials have selected bridges for construction, replacement, or rehabilitation on the basis of engineering judgement, intuition, political pressure, citizen outcry, and other subjective criteria. This method not only distorts priority selection of projects, but creates disorder in program planning and renders data collection less useful than might otherwise be the case.
1.2 DESCRIPTION OF THE STUDY

1.2.1 Objective

The objective of this study was to quantitatively define the end of functional service life for concrete bridge decks, piers, and abutments that deteriorate as a result of corrosion of the reinforcing steel. The damage level that justifies rehabilitation was to be defined quantitatively, in terms of the percentage the component surface area damaged. It was expected that the terminal damage level for each component would be a range of percent damage, rather than a single percent damage value.

1.2.2 Scope

This study considered only non-rehabilitated simply-reinforced concrete bridge components that deteriorate as a result of exposure to de-icing salts. Bridges in a marine environment also experience deterioration caused by corrosion of the reinforcing steel. However, since the nature of seawater exposure differs from that of de-icing salt exposure, terminal damage levels may differ for bridge components in marine and snowbelt environments.

The bridge components studied were decks, piers (caps and columns), and abutments. Concrete beams were excluded
because they are usually prestressed members, and thus are outside the scope of this study.

1.2.3 Research Approach

Terminal damage levels were determined from an opinion survey of state Department of Transportation (DOT) bridge engineers who make bridge rehabilitation decisions. A field study of 18 existing concrete bridges that had been designated for rehabilitation was conducted to develop concrete bridge component maps showing areas of physical damage. Deck damage maps were produced using a ground-based photogrammetry system developed in this study, while pier and abutment damage maps were drawn by hand in the field. Survey Kits based on the component damage maps were distributed to bridge engineers in 25 states that use de-icing salts. The engineers evaluated the maps and recommended when each component should be, or should have been, rehabilitated. Based on the engineers' responses, linear regression prediction models were developed to relate the recommended bridge component rehabilitation time point to the physical damage level. Based on the prediction models, two viable terminal damage levels for concrete bridge decks, and a partial terminal damage level for concrete bridge piers, were quantified.
CHAPTER 2: BACKGROUND INFORMATION

2.1 CORROSION-INDUCED DETERIORATION OF REINFORCED CONCRETE BRIDGE COMPONENTS

2.1.1 Reinforced Concrete

Mehta describes concrete as "a composite material that consists essentially of a binding medium within which are embedded particles or fragments of aggregates" [10:8]. The "binding medium" is more commonly called cement. Common concrete is made using hydraulic cement, while bituminous concrete is made using asphalt cement. In this text, concrete will be used in place of hydraulic-cement concrete, and asphalt will be used in place of bituminous concrete.

Concrete is made by mixing cement, water, aggregates, and admixtures [10:10]. Concrete hardens (cures) as a result of hydration, which Mehta describes as "chemical reactions between cement minerals and water" [10:10]. Hardened concrete is notoriously strong in compression, but weak in tension and flexure. Thus, most concrete structures, including concrete bridge components, are made of reinforced concrete [10:5], meaning that steel reinforcing bars are embedded in the concrete to provide tensile strength.
2.1.2 Reinforced Concrete Bridge Components

Reinforced concrete bridge components [7] can be broadly placed into four categories: deck, superstructure, substructure, and appurtenances. The deck provides the riding surface for traffic. A typical reinforced concrete deck is approximately eight inches thick. The steel reinforcement usually consists of two mats of reinforcing bars, top and bottom, with the top mat being closest to the riding surface. Each mat has both longitudinal and transverse bars, which typically range from 0.5 to 0.75 inches in diameter. The longitudinal bars (parallel to the direction of traffic) help minimize shrinkage and thermal cracking. The transverse bars also serve these functions in addition to their main purpose, providing structural strength. The transverse bars lie on top of the longitudinal bars, and thus chloride ions reach the top mat transverse bars first when diffusing through the cover concrete. The deck riding surface can be either bare concrete or an asphalt overlay. Only bare decks were considered in this study.

The deck is supported by the superstructure, which commonly consists of steel wide-flange beams or prestressed concrete beams aligned longitudinally. The beams are supported at each end by the bearing seat of an
abutment. Abutments and piers (intermediate deck supports) comprise the bridge substructure. This study focused on open-type piers (the most common type), which consist of a pier cap and two or more columns. Appurtenances are non-structural bridge components, such as guard rails, parapets, curbs, sidewalks, and drainage systems.

It is important to understand how de-icing salt solutions can reach each bridge component. Decks are most vulnerable to salt attack, since salts are applied directly to the riding surface. Superstructure and substructure components are better protected, since chloride-laden water from the deck must leak through deck joints to reach these components. Most decks have an expansion joint at each abutment, and many decks have an expansion joint at each pier. While these joints are made to be waterproof, they tend to leak, exposing beams, pier caps and columns to chloride-laden water. For some columns, splash water from underpass traffic is another source of de-icing salt solutions.

2.1.3 Damage Accumulation

Corrosion-induced damage accumulates on a reinforced concrete bridge component by the following process:
1. De-icing salts are applied repeatedly to the concrete surface.

2. Chloride ions from the de-icing salts diffuse to the level of the steel reinforcing bars.

3. At a threshold chloride concentration, the bars begin to corrode.

4. The corrosion products expand, exerting pressure on the concrete surrounding the bars.

5. Cracks form when the pressure exerted by corrosion products exceeds the tensile strength of the concrete.

6. The cracks cause either spalling (loss) of the surface concrete, or the formation of delaminated areas which can eventually spall.

7. Bridge maintenance crews patch spalled and delaminated areas, using either asphalt or concrete.

2.1.3.1 Diffusion and Corrosion

After repeated de-icing salt applications, soluble chloride ions from the salts diffuse through the cover concrete to the level of the reinforcing steel. Corrosion may begin when the chloride content at bar level reaches a threshold concentration estimated to be approximately 1.2
pounds per cubic yard \([11:82,12,13]\). The chloride ions initiate corrosion by destroying the passive layer of iron oxide that ordinarily protects the steel \([10:152-4]\).

Corrosion can result in the formation of any of six corrosion products, each being an oxidized version of iron (Fe) \([10:153]\). The corrosion products are expansive, and thus exert pressure on the concrete surrounding the bars. Referring to these expansive products, Mehta reports that "depending on the oxidation state, metallic iron can increase more than six times in volume" \([10:153]\).

2.1.3.2 Cracking

Cady and Weyers cite two types of cracks that can form as a result of pressure from corrosion products \([6:36,14]\). If the cover depth of concrete is about one inch or less, incline cracks are likely to form. These cracks extend from the reinforcing bar toward the concrete surface, often allowing cover concrete to spall. If the cover depth exceeds 1.25 inches, horizontal cracks are likely to form. Rather than extending to the concrete surface, horizontal cracks tend to connect from bar to bar. The result of horizontal cracking is separation, or delamination, of the cover concrete.
2.1.3.3 Delamination and Spalling

While delaminated areas (delaminations) cannot be seen on bridge component surfaces, they can be located by tapping the surface with a hammer, or by dragging chains over the surface. Delaminated concrete sounds hollow relative to non-delaminated concrete.

Delaminations can eventually become spalls. A crack, running parallel to one of the reinforcing bars, usually develops on the surface of the delaminated concrete. Then, a second surface crack often forms, transverse to and crossing the original crack. Eventually, the chunks of cover concrete defined by the cracks break loose. The resultant spalled area is usually circular in shape.

2.1.3.4 Patching

Bridge maintenance and repair of corrosion-induced damage is usually done by state personnel. Concrete is commonly used to patch bare concrete decks and substructure components, and asphalt is often used to temporarily patch spalled deck areas.

The advantage of using asphalt to patch decks is that repairs can be made with a minimum of interruption to traffic flow. The disadvantages are that asphalt patches usually result in a rough riding surface, and tend to last
only a short time. Patching with concrete takes more time, but results in a smoother and more permanent repair. A concrete saw is used to cut along the perimeter of the spalled or delaminated concrete; the unsound concrete is removed by chipping with a hammer; and fresh concrete is placed in the cavity. Since preparation is required and the concrete must be allowed to cure, patching with concrete usually interrupts traffic flow for several days.

2.1.3.5 Deterioration Indicators

The accumulation of physical damage on concrete bridge components can be described in terms of five deterioration "indicators" [2:16]: cracks, spalls, delaminations, asphalt patches, and concrete patches. The term total damage will be used to mean the summation of all areas showing deterioration indicators.

2.2 PREVIOUS EFFORTS TO DEFINE BRIDGE SERVICE LIFE

A literature review revealed several initial efforts to define service life for concrete bridge components [2:17, 54-75, 6, 8:334-7, 15:V1-V24, 16:41-5]. Each of these efforts related physical damage or some surrogate parameter to the end of service life.
2.2.1 Studies Relating Deck Condition Ratings to Age

A draft report on Bridge Management Systems [15:V1-V24] summarizes five studies which related bridge deck inspection condition ratings to deck age for large samples of bridge decks. The studies were conducted by:

- Wisconsin DOT (1983) [17]
- Massachusetts Institute of Technology (1985) [18]
- Transportation Systems Center (1985) [19]
- New York State DOT (date unknown) [20]
- Bridge Management System Demonstration Project (1987) [15:V16-V17]

The Federal Highway Administration bridge condition rating scale used in these studies ranges from zero to nine, with zero indicating a "failed condition" and nine indicating an "excellent condition" [21:14-9].

To use the deterioration curves to define the end of functional service life, a terminal condition rating would have to be designated [15:V19]. For example, on the scale from zero to nine a rating of four could be chosen as indicating the need for rehabilitation. The corresponding age at rehabilitation could then be determined from a deterioration curve. Unfortunately, choosing a terminal condition rating would be subjective, because engineers do not base their condition ratings on quantifiable criteria.
Thus, it is questionable whether the deterioration curves could provide realistic estimates of the age when rehabilitation should occur.

2.2.2 Deck Treatment Opinion Survey

In 1985, Chamberlin surveyed 30 bridge and materials engineers regarding maintenance treatments for decks [2:25-6,16:41-5]. As stated by Weyers et al., each respondent was "asked to examine 30 'ink blot' diagrams representing different degrees and patterns of deck spalling, and to indicate the type of treatment appropriate for each" [2:25]. The deck diagrams showed three distributions of spalling:

- "Spalling in random locations"
- "Spalling in several areas"
- "Spalling in a single area" [16:43]

For each distribution, ten different percentages of spalling were shown, ranging from 0.04% to 8.00% of the deck area [16:43].

According to Weyers et al., the survey responses "indicated that overlay of the entire surface is appropriate when spalling attains a level somewhere between 2.0 and 4.0 percent of the deck area" [2:25]. However, this terminal damage level based on a single
deterioration indicator may be have limited applicability since at least five deterioration indicators can be present on a deck.

2.2.3 Mean Age-at-Overlay Deck Studies

Cady and Weyers [8:334-7] and Weyers et al. [2:55-9] estimated the mean age-at-overlay for the four sets of treated decks presented in Table 1. For each set, "deck age" was plotted as a function of "cumulative percent of decks overlaid" on normal probability paper. The mean age-at-overlay was determined to be the age at which 50% of the decks had been overlaid. For all the data sets except New York, the mean age-at-overlay was based on an extrapolation of the data [2:57,8:336].

Cady and Weyers suggest that the estimated values for mean age-at-overlay (16, 23.5, 34, and 39 years) vary due to "site-specific" environmental conditions and maintenance policies [8:336]. Accordingly, the variability in these mean age-at-overlay estimates suggests that deck age is an insufficient single predictor of the end of service life for decks in all snowbelt states.
Table 1. Mean age-at-overlay estimates from sets of treated bridge decks. After Cady and Weyers [8:334-7, "MI & NY" data set]; and Weyers et al. [2:55-9, other data sets].

<table>
<thead>
<tr>
<th>State(s) Where Decks Were Located</th>
<th>Number of Decks</th>
<th>Estimated Mean Age-at-Overlay (yrs.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Michigan &amp; New York</td>
<td>Unknown</td>
<td>39</td>
</tr>
<tr>
<td>New York</td>
<td>47</td>
<td>16</td>
</tr>
<tr>
<td>Pennsylvania</td>
<td>234</td>
<td>23.5</td>
</tr>
<tr>
<td>Virginia</td>
<td>120</td>
<td>34</td>
</tr>
</tbody>
</table>

2.2.4 Mean Damage-at-Overlay Deck Studies

In 1984, Cady and Weyers estimated the mean damage-at-overlay to be 38.1% for a sample of 169 decks in Pennsylvania [2:17,§:38-40]. This estimate was based on "the application of chloride diffusion and corrosion theory considerations plus empirical data" [2:17] from the decks. In 1991, Weyers et al. estimated the mean damage-at-overlay for some of the decks in the New York data set from Table 1 [2:17]. Pre-treatment condition maps were obtained for 35 overlaid decks in the data set. Based on the damage shown on the maps, the estimated mean damage-at-overlay was found to be 22.0% for these decks [2:17].

The two estimates of mean damage-at-overlay, 38.1% and 22.0%, differ significantly. In addition, the estimates are based on decks from only two states, and
thus may not be applicable to decks in all snowbelt states.

2.2.5 Summary

As of 1991, several studies had been conducted to define the end of service life for concrete bridge decks. There were no studies found that attempted to define the end of service life for piers or abutments. While the deck studies conducted by Chamberlin and Cady and Weyers yielded preliminary data regarding deck service life, a need for further efforts to define the end of service life for concrete bridge components was indicated.
3.1 RESEARCH APPROACH

The approach used in this study to define the end of functional service life for concrete bridge components involved an opinion survey of bridge engineers who make decisions regarding concrete bridge component rehabilitation. The engineers who participated in the survey evaluated maps of deteriorated concrete bridge components showing areas of physical damage, and recommended when each component should be, or should have been, rehabilitated. The benefit of this approach was that relatively few component maps were needed to obtain responses from many engineers.

Since it was desirable for the survey respondents to evaluate bridge component maps showing realistic patterns of corrosion-induced deterioration, the component damage maps were developed from a field survey of existing deteriorated bridges thought to be near the end of their functional service life. A major concern was the time required to map the physical damage on the bridge components. Mapping decks presented the greatest challenge due to the large deck surface areas and the need for traffic control. Thus, photographic techniques were used to minimize the mapping time for decks and to provide
recorded images (photographs) from which the deck damage maps could be produced.

The research approach was conducted as follows:

1. A photographic method for recording deck damage quickly and producing deck damage maps was developed.

2. State Departments of Transportation were asked to identify candidate field study bridges which had been designated for deck rehabilitation within the past year.

3. Physical damage surveys were performed on 18 selected field study bridges from five states. Deck damage was recorded using the photographic method and substructure component damage was recorded on hand-drawn maps.

4. Deck damage maps were produced from the deck photographs using a digitizer, ERDAS imaging software [22], and a rectification program [23]. Substructure component damage maps were produced from the hand drawn field maps using AutoCAD software [24].

5. The component damage maps were evaluated by state Department of Transportation bridge engineers via an opinion survey. The survey
responses were used to define terminal damage levels for concrete bridge decks and piers.

3.2 BRIDGE DECK MAPPING METHOD

The method used to produce deck damage maps consisted of two procedures: use of a ground-based photogrammetry system (camera system) to take photographs of the damaged deck areas; and use of a digitizer, ERDAS imaging software, and a rectification program to produce plan view deck maps from the deck photographs.

The camera system consisted of a 35mm camera pointed at the deck from a fixed height (12 feet) above the deck surface. The procedure for using the system involved marking damaged deck areas with paint, placing photographic reference control points on the deck, and taking a series of deck photographs. Each photograph covered a portion of the deck defined by four control points arranged in a rectangular pattern, with a fifth control point placed inside the rectangle such that it would appear near the center of the resultant photograph. By moving the camera system along the length of the deck, photographs were taken to record the entire deck surface.

Rather than having the optical axis of the camera normal to the deck surface (vertical photograph), the
camera was tilted at a fixed angle (oblique photograph) to increase the photographic field of coverage. For each resultant photograph, the oblique (tilted) deck damage images were digitized to create a computer data file containing sets of x and y coordinate pairs which defined each image. A rectification program was used to transform the data file oblique image coordinates to horizontal (plan view) image coordinates. The rectification transformation was based on the photograph tilt angle computed from the coordinates of the digitized fifth (center) control point which appeared in each photograph.

3.2.1 Development of Camera System

The camera system had to satisfy two requirements. First, it had to provide a sufficient field of coverage. Second, the images in each photograph had to be large enough that they could be digitized with sufficient accuracy to produce a reasonably accurate plan view map.

3.2.1.1 Field of Coverage

The field of coverage is determined by the camera height, the type of photograph (vertical or oblique), and the camera lens focal length.
Vertical and Oblique Photographs

Figures 2 and 3 present vertical and oblique photographs, respectively [25, 26:28-31, 59-61, 27:106-26, 354-75]. The field of coverage is shown for each type of photograph. The variable $X$ is the depth of coverage, and the variable $Y$ is the width of coverage.

For a vertical photograph, the camera optical axis, an imaginary line that is normal to the camera film surface and goes through the center of the camera lens [25], is normal to the object plane being photographed. The resultant field of coverage is a rectangular area, with dimensions proportional to the dimensions of the camera format. For a 35mm camera, the nominal format dimensions are 35mm by 24mm. Thus, the field of coverage using a 35mm camera is a rectangular area, with the coverage width to depth ratio being 35 to 24 (1.46 to 1).

For an oblique photograph, the camera is tilted [27:354] so that the angle between the optical axis and the object plane is less than 90°. The resultant field of coverage is trapezoidal in shape and has dimensions determined partially by the extent to which the focal axis is tilted from vertical. The extent of tilt is called the tilt angle ($\omega$) [27:360]; see Figure 3. Increasing the tilt angle results in a greater depth of coverage $X$, but
Figure 2. Vertical photograph. After Johnson [25,26:28-31]; and Wolf [27:106-26].
Figure 3. Oblique photograph.
After Johnson [25,26:59-61]; and Wolf [27:354-75].
also results in greater decreases in photograph image size along the X dimension.

Focal Length

Figures 2 and 3 illustrate two spatial camera parameters that affect the field of coverage: the height of the camera above the object plane, and the tilt angle. A third critical parameter is the focal length of the camera lens. A lens having a short focal length, such as 28mm, produces a photograph having a large field of coverage, but with small images. A "zoom" lens having a long focal length, such as 70mm, produces a photograph having larger images, but with a smaller field of coverage. Thus, the task of developing a camera system involved balancing three system parameters: camera height, tilt angle, and focal length.

Minimum Allowable Field of Coverage

All of the bridge decks mapped in this study carried two lanes of traffic. Each deck was mapped by blocking traffic from one lane and shoulder, marking and photographing damaged areas, and then repeating the process on the other lane and shoulder.

A typical traffic lane is 12 feet wide, and most
shoulders are no more than 10 feet wide. Thus, the minimum allowable width of coverage for the camera system was 22 feet. In addition, it was desirable to have the greatest depth of coverage possible for each photograph, so that a deck survey time of one working day could be maintained. It was estimated that there would not be sufficient time to set up and take more than 30 deck photographs within the typical six-hour traffic control period from 9:30 am to 3:30 pm. Since two series of photographs (one for each blocked lane) would need to be taken to record the damage condition of each deck, and the majority of bridge decks are less than 300 hundred feet long, 20 feet was chosen as the working depth of coverage. Thus, a minimum field of coverage was established as having a width of coverage of 22 feet and a depth of coverage of 20 feet.

3.2.1.2 Potential Combinations of Tilt Angle and Focal Length

The next step was to identify potential combinations of camera height, tilt angle, and focal length that would provide the minimum field of coverage. Camera height was determined first. While it was desirable to elevate the camera as much as possible to increase the field of
coverage, the camera operator needed to be elevated by a platform to focus the lens and release the shutter. A camera height of 12 feet was chosen, because it was considered feasible to build and transport a camera tripod and operator platform to accommodate a camera at this height.

Next, the three common camera lens focal lengths were considered: 28mm, 50mm, and 70mm. The field of coverage was calculated for all possible focal length and tilt angle combinations (F/T combinations). The F/T combinations presented in Table 2 were found to provide a depth of coverage of at least 20 feet. Photographs of test objects were taken using these F/T combinations to determine the accuracy of the resultant rectified images for each combination.

3.2.1.3 Map Accuracy

It was desirable for each deck damage map to provide a reasonably accurate representation of the actual deck condition. To achieve reasonably accurate maps, it was necessary for the damaged area images in the deck photographs to appear at a large enough scale that they could be digitized with acceptable accuracy. Thus, it was necessary to balance the extended field of coverage
Table 2. Potential F/T combinations.

<table>
<thead>
<tr>
<th>Focal Length</th>
<th>Tilt Angles</th>
</tr>
</thead>
<tbody>
<tr>
<td>28mm</td>
<td>39° to 66°</td>
</tr>
<tr>
<td>50mm</td>
<td>51° to 75°</td>
</tr>
<tr>
<td>70mm</td>
<td>60° to 78°</td>
</tr>
</tbody>
</table>

provided by a large tilt angle with the larger image size provided by a small tilt angle.

It is important to emphasize that legitimate survey responses could have been obtained without a high level of map accuracy, since the engineers would base their evaluations on the component map damaged areas regardless of how closely they matched the actual deck damaged areas. The purpose of making the damage maps from existing bridges was simply to get realistic representations of corrosion-induced damage. Still, it was considered important for the mapping method to produce reasonably accurate maps, because such a method could have importance beyond the needs of this study. For example, State DOTs could consider refining the method to map bridge decks for routine inspections and rehabilitation quantity estimates.

Because of this potential use, minimizing the map misrepresentation error was a criterion used in developing the camera system. The misrepresentation error is the
difference between the surface area of damage on the bridge deck and the surface area of the representation of damage on the deck map. Potential sources of misrepresentation error can be identified by considering the procedure that was developed for producing the maps from the deck photographs.

**Procedure for Producing Maps from Deck Photographs**

The procedure developed for producing plan view deck damage maps from oblique deck photographs involved the use of a digitizer, ERDAS imaging software, and a rectification program. A digitizer consists of a table (tablet) and a pointing device similar to a computer mouse. To use the digitizer, a photograph is taped to the tablet surface, and the pointing device is used to trace the images in the photograph. As each image is traced, the digitizer collects pairs of $x$ and $y$ coordinates referenced to a cartesian coordinate system specified by the user. Each photograph image is thus defined by a set of coordinate pairs.

The digitized vector-based coordinate data, which "consist of points, lines, and polygons" [28:39], must be converted to raster-based pixel data [28:1-4] to calculate surface areas or print images. ERDAS software is designed
to manipulate coordinate data collected by a digitizer.

The procedure for producing deck damage maps consisted of the following steps:

1. Each photograph was enlarged to 8 inch by 10 inch size to facilitate digitizing.
2. Using the digitizer pointing device, the oblique damaged area images in each photograph were traced to create a computer coordinate file of sets of $x$ and $y$ coordinate pairs which defined the location and size of each image.
3. A rectification program was used to transform the oblique image coordinate file for each photographed deck portion to a horizontal (plan view) ground coordinate file.
4. The horizontal ground coordinate files were linked together to create a coordinate file for the entire deck.
5. The deck coordinate file consisting of vector data was converted to a file consisting of raster (pixel) data.
6. The total surface area of each type of damage represented in the deck coordinate file was calculated by multiplying the number of damage pixels by the deck surface area per pixel.
Deck maps were printed using an ink-jet printer (Tektronix model 4697). ERDAS software was used in all steps except 1 and 3. To better understand the process presented in steps 2, 3, and 4, it is necessary to be familiar with the coordinate systems and transformations shown in Figure 4.

In step 2, the digitizer produced a file containing image coordinates in millimeters, referenced to an origin established near the lower left corner of the photograph; see Figure 4A. A sample coordinate data file is presented in Appendix A. The rectification program (step 3) performed two coordinate transformations, the first being a two-dimensional transformation to a coordinate system with units of feet and the origin at the center of the photograph; see Figure 4B. The second transformation, based on the camera height, tilt angle, and lens focal length, was then performed to rectify the oblique image coordinates to horizontal ground coordinates in a system with units of feet and the origin at the base of the camera mount; see Figure 4C.

To link horizontal ground coordinate files together to make a coordinate file for the whole deck (step 4), another two-dimensional transformation was performed on each file using ERDAS commands. This transformation
Figure 4A. Origin Near Photograph Corner, Units in Millimeters.

Figure 4B. Origin at Photograph Center, Units in Feet.

Figure 4C. Origin at Base of Camera Mount, Units in Feet.

Figure 4. coordinate systems and transformations for producing rectified coordinate data files from oblique photographs.
shifted the coordinate file origin from the base of the camera mount to an origin selected for the whole deck; see Figure 5. For example, for the first photograph taken of the right-hand strip of the deck, the transformation would shift the coordinates of the four corner control points (CPs) to the following nominal coordinates, where X is the total width of the lane and shoulder in feet:

Upper Left CP: (0,20)   Upper Right CP: (X,20)
Lower Left CP: (0,0)    Lower Right CP: (X,0)

In step 5, the vector-based deck coordinate file was converted to a raster-based deck coordinate file. The user specifies the pixel size for the rasterization process. Specifying an infinitely small pixel size results in raster images that precisely duplicate the vector images, but the raster file size can be unmanageably large. Specifying a larger pixel size reduces the size of the raster file, but results in blocky representations of the vector images. A rasterization pixel size of 0.01 by 0.01 feet (horizontal ground coordinates) was initially chosen for the deck maps.
Figure 5. Two-dimensional coordinate transformation for creating a whole-deck coordinate data file from individual rectified coordinate data files.
Sources of Misrepresentation Error

The following potential sources of misrepresentation error were identified for the mapping method:

- Disagreement between actual and measured control point coordinates.
- Internal misalignments and distortions within the camera.
- Variances in camera lens focal length.
- Human digitizing error.
- Blockiness associated with rasterization.
- Limited printer resolution.

Control point and digitizing errors are random, while the other errors are likely to be systematic [26:7-8]. Systematic errors are consistently positive or negative. For example, since a raster-based image is blocky compared to the vector-based image from which it was produced, the rasterization process tends to cause only positive errors (increases in surface area).

It was expected that the camera errors would be negligible because a high-quality camera was being used. Also, the true camera lens fixed focal lengths were calculated from photograph image dimensions of objects photographed at a measured distance. However, the control point, digitizing, rasterization, and printer resolution
errors were considered likely to affect map accuracy.

Since it would be difficult to accurately estimate the value of each error, the total misrepresentation error from all sources was calculated for each potential F/T combination. The procedure involved taking photographs of test objects, digitizing and rectifying the photograph test object images, and calculating the surface areas of the rectified images. The misrepresentation error was determined by comparing the known surface areas of the test objects to the calculated surface areas of the rectified test object images.

3.2.1.4 Photographs of Test Objects Using Potential F/T Combinations

The total misrepresentation error was determined by photographing paper circles having a diameter of 13.5 inches. The resultant surface area of each circle, one square foot, is comparable to the size of the smallest spalls typically found on a bridge deck. Photographs were taken in an indoor recreation facility, with the camera mounted to scaffolding at a height of 12 feet above the floor. To simulate a lane and shoulder of a bridge deck, surveying ribbon was taped on the floor to define a rectangular area 22 feet wide by 100 feet long. The
"spalls" (paper circles) were placed every 3.3 feet along the length of the "deck", and the scaffolding to which the camera was mounted was placed at one end of the simulated deck surface.

A Minolta X-700 camera was used to take photographs of the simulated deck using the F/T combinations presented in Table 2. Photographs were taken at increments of 3° of tilt angle; for example, using a 28mm lens, photographs were taken at tilt angles of 39° to 66° at increments of 3°. A total of ten photographs were taken using a 28mm lens, nine using a 50mm lens, and seven using a 70mm lens.

Of the resultant photographs, those taken using the 50mm and 70mm lenses were immediately eliminated from consideration, because the minimum width of coverage occurred at distances of 30 feet or greater from the base of the camera mount. The photograph images of circles at these distances were very small, and thus would be difficult to digitize accurately.

Of the photographs using the 28mm lens, those using tilt angles of 51° and 54° most clearly presented the circle images and had acceptable fields of coverage. Misrepresentation errors were calculated for both of these photographs to determine the optimum F/T combination.
3.2.1.5 Selection of Optimum F/T Combination

The two photographs, taken using a 28mm lens at tilt angles of 51° and 54°, were enlarged to 8 inch by 10 inch size to make digitizing easier. Two workers (who later digitized all of the deck photographs from the field study) individually digitized the oblique circle images in each photograph three times, producing a total of six image coordinate files for each photograph. The procedure described previously was used to produce a rectified raster file from each oblique coordinate file. Thus, there were six computed surface areas for the rectified representation of each circle that appeared in the photographs. The mean of the six computed surface areas was determined for each circle.

In both photographs, the minimum width of coverage (22 feet) occurred at a distance of 13 feet from the base of the camera mount. Thus, the effective depth of coverage $X_E$ began at a near distance $X_{E,n}$ of 13 feet. In the photograph with a tilt angle of 51°, circles could be seen up to a far distance $X_{E,f}$ of about 40 feet from the base of the camera mount. The effective depth of coverage is computed as follows:

$$X_E = X_{E,f} - X_{E,n} = 40 \text{ feet} - 13 \text{ feet} = 27 \text{ feet}$$
Table 3 presents the mean of six computed surface areas for the rectified circles at three distances $D$ from $X_{E,n}$.

The two F/T combinations proved to have similar merit. While the mean surface area at $D = 25$ feet is noticeably higher for the photograph using a tilt angle of $54^\circ$, the maximum misrepresentation error within the chosen depth of field (20 feet) is approximately the same for the two photographs (close to 20%). Still, when the rectified raster files were viewed on a computer monitor, it was observed that the rectified circle images from the $51^\circ$ tilt angle photograph were somewhat less distorted in appearance than those from the other photograph. This difference in appearance is not surprising, because the circle images were slightly larger in the $51^\circ$ tilt angle photograph than they were in the other photograph, meaning that the random digitizing errors were probably smaller for the $51^\circ$ tilt angle photograph. Thus, the field survey deck photographs were taken using a 28mm lens at a nominal tilt angle of $51^\circ$.

3.2.1.6 Discussion of Test Photograph Misrepresentation Errors

All of the mean computed surface areas shown in Table 3 are greater than one square foot, the actual size
Table 3. Misrepresentation error data for two potential F/T combinations.

<table>
<thead>
<tr>
<th>Lens Focal Length</th>
<th>Camera Tilt Angle</th>
<th>Mean Computed Area of Circles at D =</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>15 feet</td>
</tr>
<tr>
<td>28mm</td>
<td>51°</td>
<td>1.19 sf</td>
</tr>
<tr>
<td>28mm</td>
<td>54°</td>
<td>1.20 sf</td>
</tr>
</tbody>
</table>

Note: Areas were computed from images rasterized using a pixel size of 0.01 by 0.01 feet (horizontal ground coordinates).

of the circles. Also, for each photograph the misrepresentation error is greatest for the circles farthest from the camera (i.e., is greatest for the smallest photograph images). Thus, it is probable that the primary source of misrepresentation error is the rasterization process, which tends to increase the surface areas of vector-based images, and that the secondary source of error is the digitizing process.

3.2.1.7 Misrepresentation Error for Deck Damage Maps

The test photograph oblique image coordinate files were rasterized using a pixel size of 0.01 by 0.01 feet. The resultant rectified pixel files were viewed on a high-resolution computer monitor rather than being printed, because the Tektronix ink-jet printer to be used for...
printing the deck damage maps was not available at the time the F/T combinations were evaluated. Later in the study, when the deck maps were being printed, it was discovered that the resolution of the printer was considerably less than the resolution of the computer monitor. Due to limited printer resolution, using pixel sizes smaller than 0.04 by 0.04 feet yielded no improvement in map accuracy. Accordingly, this pixel size was used for rasterization, since using a pixel size of 0.01 by 0.01 feet would have unnecessarily increased the size of the deck raster files.

Since a larger pixel size was used, the misrepresentation error for the actual deck maps was slightly greater than the errors shown in Table 3. To estimate the error for the deck maps, two of the rectified image coordinate files for the 28mm/51° test photograph were rasterized using a pixel size of 0.04 by 0.04 feet. The mean of two computed surface areas for circles at $D = 20$ feet was 1.24 square feet, slightly greater than the computed mean surface area (1.17 square feet) using a pixel size of 0.01 by 0.01 feet. The increase in mean computed surface area corresponding to a larger rasterization pixel size indicates that rasterization errors are systematic and positive. Based on the computed
mean surface area of 1.24 square feet, it is estimated that the maximum mean misrepresentation error for the deck damage maps produced in this study is about 24% for a one-square-foot area.

While this error may seem large, it is important to realize that the damaged areas found on bridge decks typically have surface areas much greater than one square foot. Thus, a maximum error of 24% for a small area would probably mean that the average error for all damaged areas would be less, perhaps between 10% and 15%. Also, the component maps produced in this study were printed at a small scale for practical reasons, and thus a 24% difference in surface area for a small area of damage was difficult to detect when looking at the maps. Finally, for future applications the misrepresentation error could be reduced by using a higher-resolution printer capable of supporting a smaller rasterization pixel size.

3.2.2 Rectification Program

A rectification program written by Johnson [23] was used to transform oblique image coordinate files to horizontal image coordinate files. A list of the rectification program code is presented in Appendix A.
3.2.2.1 Program Logic

The rectification program works as follows:

1. After digitizing a deck photograph, the user inputs the name of the digitized data file, which consists of pairs of x and y coordinates defining oblique deck damage images.

2. The user inputs the height of the camera, the focal length, and the distance from the base of the camera mount to a control point that appears in the photograph.

3. The coordinates of the true center of the photograph are calculated.

4. Each pair of x and y coordinates in the data file undergoes a two-dimensional coordinate transformation, which converts the coordinate units from millimeters to feet and places the coordinate system origin at the center of the photograph.

5. The actual photograph tilt angle is calculated from the coordinates of the digitized fifth (center) control point.

6. Each pair of x and y coordinates in the data file undergoes a rectification transformation based on the calculated tilt angle. The oblique
image coordinates are transformed to horizontal image coordinates.

7. An output horizontal coordinate data file is created.

The actual tilt angle cannot be calculated (step 5) unless a control point placed at a known location appears in the photograph.

3.2.2.2 Use of Control Points During Field Survey

A tripod was built to hold the camera at a fixed nominal tilt angle of 51°. However, it was anticipated that the actual tilt angle would vary slightly for each photograph, due to a lack of rigidity in the 12-foot tripod. To maximize the accuracy of the second coordinate transformation (step 6), the actual tilt angle for each photograph was calculated by the rectification program (step 5).

For each photographed deck region, the fifth control point was placed on the deck at a measured distance from the base of the camera mount, so that it would appear near the center of the resultant photograph. The control point was digitized along with the other photograph images to put an x and y coordinate for the control point into the data file. The true control point coordinates were read
by the rectification program and compared to control point coordinates that would be expected if the tilt angle was exactly 51°.

Figure 6 presents an example camera setup to illustrate this process. The control point distance and camera height are both 12 feet, so that the camera, the base of the camera mount, and the control point form a triangle with interior angles of 45°, 45°, and 90°. The camera is aimed at the control point, and a photograph is taken. If the control point appears exactly at the center of the photograph, a tilt angle of 45° would be calculated. However, if the control point appears toward the bottom of the photograph, the camera was aimed too high and the calculated tilt angle would be greater than 45°.

For the 51° tilt angle used in this study, the control point distance from the base of the camera mount was calculated as follows:

\[(12 \text{ feet height}) \times (\tan 51°) = 14.8 \text{ feet}\]

Thus, for all of the field survey deck photographs a control point was placed on the deck 14.8 feet from the
Figure 6. Camera setup with control point used to calculate the actual tilt angle.
base of the camera mount.

The coordinates for the true center of each photograph were calculated in step 3 to provide a point of reference for evaluating the true control point coordinates. The corner coordinates of a photographic negative taken using the project camera were precisely determined using a measuring device called a comparator. While the corner coordinates for a 35mm camera negative define nominal dimensions of 35mm by 24mm, the actual negative dimensions vary slightly from camera to camera. The true center of the negative was determined to be the intersection point of diagonal lines connecting opposite negative corners.

The four corner points of each deck photograph were digitized along with the deck damage images. After fitting the photograph corner coordinates to the negative corner coordinates, the rectification program determined the true center of each photograph based on the coordinates of the true center of the negative. The actual tilt angle was then calculated for each photograph (step 5), based on the difference between the actual control point image displacement from the photograph center and the computed 51° control point image displacement from the photograph center.
3.3 **FIELD STUDY**

Damage surveys of deteriorated concrete bridge decks, piers, and abutments were conducted during a field study of 18 concrete bridges. Deck damage was recorded using the photographic mapping method, while damage on piers and abutments was recorded on hand-drawn maps. The field study was preceded by the following preparation activities:

1. Criteria were developed for selecting bridges to study.

2. State Departments of Transportation (DOTs) were asked to identify candidate bridges meeting the specified criteria.

3. From approximately 60 candidate bridges identified, 18 were selected for inclusion in the field study.

3.3.1 **Criteria for Candidate Bridges**

A candidate bridge for inclusion in the field study had to have a deck that:

1. had been designated for rehabilitation within the past year;

2. had a bare concrete riding surface (not overlaid with asphalt);
3. carried two lanes of traffic; and
4. was less than 300 feet long.

It was important for each field study bridge to show significant physical damage caused by the corrosion of steel in concrete. The deck condition was chosen as the damage criterion for bridge selection because the deck was considered to be the bridge component that typically requires rehabilitation first. To insure that each deck would show a level of damage reasonably close to the terminal damage level, only decks that had been designated for rehabilitation by State DOT personnel within the past year were considered.

Only two-lane bridges less than 300 feet long were considered for study because it was estimated that bridges having additional lanes or longer spans would be difficult to map in one day, the desired mapping time period. Also, a majority of bridges fall into the category of two-lane bridges under 300 feet.

3.3.2 Identification of Candidate Bridges

Candidate bridges were sought from eight states, because it was considered important to survey bridges from different geographic locations and environmental exposure conditions so that the resultant damage maps would
represent a realistic sample of the deteriorated bridge components that exist in the United States.

3.3.2.1 Letters to State Departments of Transportation

Letters requesting identification of 10 to 36 candidate bridges were sent to the Departments of Transportation of Maryland, Michigan, New York, Ohio, Pennsylvania, Virginia, West Virginia, and Wisconsin. The following information was requested for each bridge:

1. The name of the bridge and its location shown on a county map.
2. A description of the components designated for rehabilitation.
3. The date the bridge was constructed and put into service.
4. The mean annual snowfall and the traffic volume.
5. The approximate date of the scheduled rehabilitation work.

No candidate bridges were identified by Maryland, New York, or West Virginia. The candidate bridges identified by the remaining five states were considered for preliminary site visits.
3.3.2.2 Preliminary Site Visits

Visits were made to approximately 60 candidate bridges among the states of Michigan, Ohio, Pennsylvania, Virginia, and Wisconsin. The visits were made to determine:

1. Accuracy of the submitted bridge information.
2. Working safety concerns.
3. Condition of the substructure components.

The condition of the substructure components was an important consideration, because it was preferable to study bridges from which substructure component damage maps could be made for inclusion in the opinion survey.

3.3.3 Selection of Bridges to Study

Eighteen of the candidate bridges were selected for study, based on the following considerations:

1. Observations made about each bridge during the preliminary site visits.
2. Geographic distribution of the bridges among the five states.
3. Distribution of the bridges among ranges of environmental conditions.

A field study matrix proposed by Weyers et al. [2:37-9] was used to distribute the bridges among ranges of two
"measures of environmental severity" [2:37]: mean annual snowfall and traffic volume. The mean annual snowfall (MAS), expressed in inches per year, is likely to be roughly proportional to the amount of de-icing salts applied to a bridge deck [2:37]. The volume of traffic, expressed in vehicles per day, is likely to affect the rate at which delaminations break up into spalls and may also affect the frequency of de-icing salt applications [2:37]. The volume of traffic is commonly measured as the average annual daily traffic (AADT), the average number of vehicles per day that drive over the deck based on traffic counts taken at selected time intervals over a one year period.

The nine-cell field study matrix consists of the following groupings for MAS and AADT:

MAS (inches/year):
- 0 - 20
- > 20 - 50
- > 50

AADT (vehicles/day):
- 0 - 8,000
- > 8,000 - 16,000
- > 16,000

Weyers et al. state that the MAS groupings were based on a chart showing the severity of vehicle corrosion for different regions of the United States, while the AADT groupings were primarily based on judgement [2:38].
Efforts were made to select a set of study bridges that would be evenly distributed among the nine cells. Figure 7 presents the resultant field study matrix for the 18 bridges that were surveyed for damage. The abbreviated bridge names are based on the state and order of inspection; for example, VA-1 was the first Virginia bridge inspected. As shown in Figure 7, an equal distribution of bridges (two per cell) was not achieved from the list of recommended candidate bridges. Few of the candidate bridges had an AADT greater than 16,000 vehicles per day. However, the bridges were distributed well among ranges of snowfall, and thus a reasonable overall distribution was achieved. Table 4 presents the location, AADT, and MAS for each bridge included in the field study.

3.3.4 Bridge Component Damage Surveys

The damage surveys consisted of mapping all damage found on the decks, piers, and abutments of the 18 bridges presented in Table 4. A crew of three workers built field equipment, conducted the damage surveys, and digitized the deck photographs. A van pulling a flat-bed trailer was used to transport the workers and equipment to each bridge.
Figure 7. Field study matrix for 18 concrete bridges that were surveyed for damage. After Weyers et al. [2:37-9].
Table 4. Locations, estimated average annual daily traffic, and estimated mean annual snowfall for 18 concrete bridges that were surveyed for damage.

<table>
<thead>
<tr>
<th>Bridge Name</th>
<th>County Located</th>
<th>Location of Bridge</th>
<th>Est. AADT</th>
<th>Est. MAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>VA-1</td>
<td>Smyth</td>
<td>I-81 NB over Rte. F-010</td>
<td>8600</td>
<td>&lt; 20</td>
</tr>
<tr>
<td>VA-2</td>
<td>Rockbridge</td>
<td>I-81 SB over Route 710</td>
<td>12500</td>
<td>&lt; 20</td>
</tr>
<tr>
<td>VA-3</td>
<td>Fauquier</td>
<td>Rte. 17 over Crooked Run</td>
<td>5200</td>
<td>&lt; 20</td>
</tr>
<tr>
<td>PA-1</td>
<td>Erie</td>
<td>I-79 NB over Camp Road</td>
<td>5600</td>
<td>100</td>
</tr>
<tr>
<td>PA-2</td>
<td>Luzerne</td>
<td>SR 3034 over I-81</td>
<td>2500</td>
<td>50</td>
</tr>
<tr>
<td>MI-1</td>
<td>Allegan</td>
<td>N. Shore Dr. over I-196</td>
<td>4500</td>
<td>40</td>
</tr>
<tr>
<td>MI-2</td>
<td>Clinton</td>
<td>State Rd. over US-127</td>
<td>3300</td>
<td>40</td>
</tr>
<tr>
<td>MI-3</td>
<td>Gratiot</td>
<td>US-27 NB over Polk Rd.</td>
<td>5400</td>
<td>76</td>
</tr>
<tr>
<td>WI-1</td>
<td>Dane</td>
<td>Maple Grove Rd. over I-90</td>
<td>100</td>
<td>42</td>
</tr>
<tr>
<td>WI-2</td>
<td>Dane</td>
<td>US-14 EB over McCoy Rd.</td>
<td>4000</td>
<td>42</td>
</tr>
<tr>
<td>WI-3</td>
<td>Columbia</td>
<td>CTH-O over STH-78</td>
<td>300</td>
<td>42</td>
</tr>
<tr>
<td>WI-4</td>
<td>Columbia</td>
<td>STH-60 over Wis. River</td>
<td>2600</td>
<td>42</td>
</tr>
<tr>
<td>OH-1</td>
<td>Ross</td>
<td>Rte. 23 EB over US-50</td>
<td>15400</td>
<td>15</td>
</tr>
<tr>
<td>OH-2</td>
<td>Ross</td>
<td>Rte. 23 WB over US-50</td>
<td>15400</td>
<td>15</td>
</tr>
<tr>
<td>OH-3</td>
<td>Franklin</td>
<td>Winchester Pike over USR-33</td>
<td>11500</td>
<td>22</td>
</tr>
<tr>
<td>OH-4</td>
<td>Lorain</td>
<td>Rte. 2 over SR-58</td>
<td>31500</td>
<td>60</td>
</tr>
<tr>
<td>OH-5</td>
<td>Lorain</td>
<td>Rte. 20 over Railroad</td>
<td>13600</td>
<td>60</td>
</tr>
<tr>
<td>OH-6</td>
<td>Lorain</td>
<td>Rte. 20 over Grafton Rd.</td>
<td>15500</td>
<td>60</td>
</tr>
</tbody>
</table>

Note: AADT = average annual daily traffic (vehicles/day). MAS = mean annual snowfall (inches/year).
3.3.4.1 Deck Damage Surveys

Traffic control was provided by the State DOTs. The steps listed below were used to take deck photographs from which damage maps were later produced:

1. Traffic control was set up to block traffic from one bridge lane and shoulder (one longitudinal photographic strip).

2. Hammers and drag chains were used to locate areas of delaminated concrete, which were outlined on the deck using lumber crayon.

3. Different colors of temporary paint were applied to the deck surface to outline spalls, delaminations, cracks, asphalt patches, and concrete patches. Roller-type handles, with roller heads two inches wide, were used to apply the paint.

4. After all painting was done, deck photographs were taken to record the outlined damage areas; see Figure 8. For each photograph, four reference control points were placed on the deck in a rectangle pattern to define the field of coverage. Each control point was a flat square piece of wood, six inches on a side, with its center marked by crossed lines. A fifth control
Figure 8. Deck damage photograph, showing damaged areas outlined with paint and five reference control points.
point was placed with its center 14.8 feet from the base of the camera mount, as discussed in section 3.2.2.2. A sign was placed on the deck to identify the portion being photographed.

5. Two photographs were taken of each deck portion, using the camera system developed in this study.

6. Steps 4 and 5 were repeated every 20 feet along the length of the deck.

7. Steps 1 through 6 were repeated on the other longitudinal half of the deck.

The drag chains used to located delaminations (step 2) consisted of wooden or metal handles with two to four chains attached by pieces of cord. While it is often difficult to locate the precise boundaries of a delaminated area, the general size and shape of each area can be determined.

The damaged deck areas were outlined with paint (step 3) so that they would be easy to see in the photographs. The selected paint type, which was determined to fade within several days of application, was a mix of 50% water-base Liquid Temp Poster Paint (Palmer Paint Products, Inc., Troy, Michigan) and 50% water. Five paint colors were used, one for each deterioration indicator: spalls, delaminations, cracks, asphalt patches,
and concrete patches.

The camera system consisted of a collapsible tripod used to elevate the camera 12 feet from the deck surface, and a platform used to elevate the camera operator. The tripod was constructed of six-foot metal sections, each piece L-shaped in cross-section with holes drilled along its length. The tripod could be assembled in about ten minutes by bolting the metal sections together. A metal bracket fastened to the top of the tripod held the camera facing downward and oriented with its optical axis tilted approximately 51° from vertical.

The platform used to elevate the camera operator was built on a small trailer. The trailer had a single axle with two wheels, a flat bed measuring six feet by ten feet, and a hitch so it could be pulled by the van. A third wheel was welded to the hitch so that the trailer bed would be horizontal when unhitched from the van. The platform, which resembled a small staircase, was attached to the rear end of the trailer bed. The trailer was light enough that it could be moved by two people. To advance along the deck (step 6) after photographing each deck portion, two workers carried the tripod forward 20 feet and then pushed the trailer into position behind the tripod. It typically took about six hours to survey an
entire deck using the described procedure.

3.3.4.2 Substructure Component Damage Surveys

Maps showing cracks, spalls, and concrete patches on substructure components were drawn by hand, since the relatively small component surface areas did not necessitate the use of photography. In addition, it was not feasible to survey piers using photography because the workers were unable to reach damaged areas to outline them with paint without some type of elevating equipment. Delaminated areas were not identified due to the lack of access.

For piers, all column and pier cap surfaces were surveyed except for the horizontal top surface of the cap, which could not be seen. The abutment surfaces that were surveyed were the breast wall, beam seat, and back wall.

A scale drawing of each component was made on grid paper, and then the damaged areas were measured and reproduced on the scale drawing. For abutments, damaged areas were simply measured using a tape measure. For column and pier cap surfaces that could not be reached, measurements were estimated using a flat square wooden frame, three feet on a side, that was lifted to the damaged area using a metal pole. The frame had strings
tied across it to form a grid of squares six inches on a side. As one worker held the frame in front of the damaged area, another reproduced the damaged area on the scale drawing.

3.4 OPINION SURVEY OF BRIDGE ENGINEERS

Conducting the opinion survey of bridge engineers involved the following three tasks:

- Printing component maps from the field photographs and drawings.
- Designing the Survey Kit.
- Distributing Survey Kits to bridge engineers.

3.4.1 Printing Bridge Component Damage Maps

3.4.1.1 Deck Damage Maps

Deck maps were produced from the deck photographs using the procedure outlined on pages 33-4. Eight map colors were chosen to represent spalls, delaminations, cracks, asphalt patches, concrete patches, border and joint lines, white lane lines, and yellow lane lines. The background deck color was white, the color of the printer paper.

A literature review was conducted to select map
colors that would be individually distinguishable, without having some of the colors overpowering others to the point of biasing the respondents. For example, objects colored red (an advancing color) tend to be more noticeable than objects colored blue (a retreating color) [29:309,315]. More generally, it is common knowledge that objects having light colors appear to be relatively larger than objects having dark colors [29:315].

In addition, efforts were made to avoid map color combinations that might be confusing to some respondents. Glass et al., citing other research [30,31], state that "about 8 to 10 percent of adult males (caucasian)" in this country "are color defective" [32:12]. According to Glass et al., people who are color defective have difficulty distinguishing between certain colors, including the following three pairs [32:13]:

- Red and blue-green
- Purple and greenish-blue
- Blue and green

Thus, the deck map colors were selected based on the following criteria:

- Colors distinguishable by brightness [29:312-3]
- Avoid colors that could bias the respondents
• Avoid potentially confusing color combinations

ERDAS allows the user to create original colors from the three additive primary colors: red, green, and blue \[29:307\]. The colors selected for the deck maps, which include both ERDAS default colors and original colors, are described in Table 5. Figure 9 presents three of the 18 deck damage maps that were used in the opinion survey.

3.4.1.2 Substructure Component Damage Maps

It was observed during the field study that most of the bridges showed relatively less damage on the substructure components than on the deck. Of the substructure components surveyed for damage, only 11 piers and 6 abutments were considered to have enough damage to be included in the opinion survey. The hand-drawn field maps for these 17 components were re-drawn using AutoCAD software. Rather than being shown separately, the pier caps and columns were drawn together as a complete pier, because it was considered likely that engineers evaluate these sub-components as a unit.

A Hewlett-Packard plotter was used in the preparation of the opinion survey substructure component maps. Plotting pens were selected to approximate the colors used
Table 5. Colors selected for opinion survey deck damage maps.

<table>
<thead>
<tr>
<th>Deck Component</th>
<th>Description of Color</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bare Deck</td>
<td>White</td>
</tr>
<tr>
<td>Spalls</td>
<td>Medium yellow-green</td>
</tr>
<tr>
<td>Delaminations</td>
<td>Medium purple</td>
</tr>
<tr>
<td>Cracks</td>
<td>Medium blue</td>
</tr>
<tr>
<td>Asphalt Patches</td>
<td>Dark purple, red tint</td>
</tr>
<tr>
<td>Concrete Patches</td>
<td>Light tan</td>
</tr>
<tr>
<td>Borders and Joints</td>
<td>Black, green tint</td>
</tr>
<tr>
<td>Yellow lane lines</td>
<td>Light yellow-orange</td>
</tr>
<tr>
<td>White lane lines</td>
<td>Light blue-green-gray</td>
</tr>
</tbody>
</table>
Figure 9. Photograph of three deck damage maps used in the bridge engineer opinion survey.
for the deck maps. Figures 10 and 11 present black-and-white copies of a pier damage map and an abutment damage map, respectively, that were used in the opinion survey.

3.4.2 Development of Survey Kit

A Survey Kit to be distributed to bridge engineers was developed based on the component damage maps. The following sections describe the general logic used in the development of the Kit. Individual Survey Kit items and the engineers' responses are presented in Chapter 4. A complete copy of the Survey Kit is presented in Appendix B.

3.4.2.1 Purpose of Survey Kit

The purpose of the Survey Kit was to obtain damage map evaluation responses which could be used to quantify terminal damage levels for concrete bridge components. An important consideration was the type of evaluation responses that should be elicited to achieve this purpose. One type of response would be a condition rating, which is how engineers typically evaluate bridges during an inspection. Unfortunately, while consistent with engineers' experience, condition ratings reflect only the bridge condition at the present time and singularly cannot
Figure 10A. Pier damage map used in the bridge engineer opinion survey.
Figure 10B. Pier damage map used in the bridge engineer opinion survey (continued).
Figure 11. Abutment damage map used in the bridge engineer opinion survey.
be used to determine the bridge condition at a time point in the past or future.

3.4.2.2 Concept of the "Time to Rehabilitate"

The Cady-Weyers corrosion-deterioration model for concrete bridges (refer to Figure 1) presents the magnitude of cumulative deterioration as a function of time. Thus, it was considered important for the engineers' responses to be referenced to a time continuum, since this would allow development of bridge component prediction models relating the rehabilitation time point to the level of physical damage. Accordingly, the engineers were asked to recommend for each survey bridge component the Time to Rehabilitate (TTR), defined in the Survey Kit as follows:

Assume that every concrete bridge component exposed to de-icing salts eventually deteriorates to a physical condition that justifies rehabilitation. We define this physical condition as the Rehabilitation Condition.

The "true" Rehabilitation Condition is reached when the component has reached the end of its functional service life, and significant correction is necessary to return it to an acceptable level of service.

The Time to Rehabilitate is the time when a concrete bridge component reaches its Rehabilitation Condition. It may be in the past, present, or future. For example:
The Time to Rehabilitate was in the past: "The component should have been rehabilitated about five years ago."

The Time to Rehabilitate is in the present: "The component should be rehabilitated now."

The Time to Rehabilitate is in the future: "The component should be rehabilitated in about five years."

The Rehabilitation Condition (a measure of physical damage) is a point on the Y-axis of the Cady-Weyers model, while the Time to Rehabilitate is a point on the X-axis.

The engineers were asked to recommend the Time to Rehabilitate by choosing a response from the following time scale having increments of two years:

A. It will be more than 20 years before this bridge component should be rehabilitated.

B. This bridge component should be rehabilitated in about 20 years.

C. This bridge component should be rehabilitated in about 18 years.

L. This bridge component should be rehabilitated now.

U. This bridge component should have been rehabilitated about 18 years ago.
V. This bridge component should have been rehabilitated about 20 years ago.

W. This bridge component should have been rehabilitated more than 20 years ago.

This time scale ranges from 20 years before the Rehabilitation Condition to 20 years beyond the Rehabilitation Condition. Two years was considered to be the shortest realistic time interval that the engineers could use to estimate the Time to Rehabilitate.

To facilitate statistical analysis, the engineers' bridge component TTR responses were converted to a discrete numerical scale from -20 (before the Rehabilitation Condition) to +20 (beyond the Rehabilitation Condition), as follows:

<table>
<thead>
<tr>
<th>TTR response:</th>
<th>-20</th>
<th>0</th>
<th>+20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rehabilitate:</td>
<td>In Past</td>
<td>In Future</td>
<td>Now</td>
</tr>
</tbody>
</table>

The engineers were given the age of each bridge component they evaluated, so that they could estimate the rate of physical deterioration and thus estimate the Time to Rehabilitate. For each component, the engineers were asked to make two TTR recommendations: one based on Local Standards and the other based on Snowbelt Standards.
3.4.2.3 Concepts of Local Standards and Snowbelt Standards

It was reasoned that since the Rehabilitation Condition is a subjective estimate, it may vary considerably from one engineering district to another. This hypothesis is supported by the wide variance in damage levels observed on the 18 decks in this study. While all of the decks had been designated for rehabilitation within the past year, the total deck damage area percentages calculated from the deck maps ranged from 1.0% to 29.8%. Thus, it was considered unlikely that the engineers' TTR responses using Local Standards would form a strong consensus about the Rehabilitation Condition. Accordingly, the engineers were asked to estimate the Rehabilitation Condition using both Local Standards and Snowbelt Standards, defined in the Survey Kit as follows:

"LOCAL STANDARDS Rehabilitation Condition"

You are familiar with the physical condition of a bridge component at the time it is rehabilitated in your engineering district. This is the Local Standards Rehabilitation Condition.

"SNOWBELT STANDARDS Rehabilitation Condition"

Assume you are a member of a committee consisting of all bridge engineers from the snowbelt states of the U.S. This large committee is responsible for reaching a consensus concerning the Rehabilitation Condition for decks, piers, and abutments.
The committee is aware that there are approximately 60,000 bridges in the United States whose decks could be described as "badly deteriorated". Many bridges also have "badly deteriorated" substructure components.

The "average" availability of federal funds for bridge rehabilitation is discussed. It is agreed that not every bridge component showing some deterioration should be rehabilitated immediately. However, it is also agreed that the public expects a reasonable level of service from bridges.

After a heated debate, the committee defines, for each bridge component, a physical condition that justifies rehabilitation. This is the Snowbelt Standards rehabilitation condition. You will be asked to estimate what the Snowbelt Standards Rehabilitation Condition would probably be for each component.

We are not asking you to try to guess what other snowbelt states think about rehabilitation; that would be impossible. Instead, we ask that you estimate standards that you think are desirable and reasonable, and could be applied to all snowbelt states.

The difference between Local Standards and Snowbelt Standards could be described as the difference between "current practices" and "recommended practices".

The following is an example Survey Kit item which asks the respondent to make TTR recommendations for a bare concrete deck:

You will be asked to examine this deck map and decide if the bridge deck should have been rehabilitated at some time in the past; should be rehabilitated now; or should be rehabilitated at some time in the future.
For decks, we define rehabilitation as REMOVAL OF UNSOUND CONCRETE, PATCHING, AND OVERLAY.

Refer to the deck map to assess the PRESENT PHYSICAL CONDITION of this deck. Consider the age of the deck to estimate the RATE at which it is deteriorating.

Consider the PRESENT PHYSICAL CONDITION, RATE, and TRAFFIC INFORMATION to answer items 1 and 2.

1. Evaluation Relative to the Local Standards Rehabilitation Condition

Estimate the Local Standards Rehabilitation Condition for concrete bridge decks. Relative to the Local Standards Rehabilitation Condition of your engineering district, when do you think this deck should have been, or should be, rehabilitated?

Select the letter of your answer from the pink sheets "ANSWER CHOICES FOR THE TIME TO REHABILITATE", and write it below.

The Time to Rehabilitate using Local Standards:

2. Evaluation Relative to the Snowbelt Standards Rehabilitation Condition

Estimate the Snowbelt Standards Rehabilitation Condition for concrete bridge decks. Relative to the Snowbelt Standards Rehabilitation Condition, when do you think this deck should have been, or should be, rehabilitated?

Select the letter of your answer from the pink sheets "ANSWER CHOICES FOR THE TIME TO REHABILITATE", and write it below.

The Time to Rehabilitate using Snowbelt Standards:
3.4.2.4 Survey Kit Layout

Each Survey Kit consisted of an instruction packet and five work packets; see Appendix A. Packets 1 through 3 addressed the evaluation of damage maps for decks; Packet 4 addressed the evaluation of damage maps for substructure components. Packet 5 included summary items, and requested respondent background information.

The Survey Kit was designed to take between 75 and 90 minutes to complete. Accordingly, each respondent was asked to evaluate damage maps for three decks, two piers, and one abutment. Since approximately the same proportions of damage maps for decks, piers, and abutments were included in the opinion survey (18, 11, and 6, respectively), it was expected that approximately the same number of responses would be received for each damage map.

Information Provided to Respondents

The following information was provided for each deck:

- The age of the deck.
- The average annual daily traffic volume (AADT).
- The estimated average traffic speed.

For piers and abutments, only the age was provided.

The age was provided for all of the bridge components
so that the respondent could estimate the rate of deterioration. The AADT and typical speed of traffic were provided for decks so that the respondent could estimate a deck usage factor. It is reasonable to expect an engineer to be most concerned about a damaged bridge deck if many vehicles cross it at high speeds. The estimated average traffic speed was expressed as "greater than 45 mph" or "less than 45 mph".

During efforts to verify this support information for each deck, it was discovered that one of the decks surveyed, VA-2, had been overlaid with concrete in the past. Since the map for this deck satisfied the criterion of showing a realistic pattern of corrosion-induced damage, it was included in the survey and was presented to the respondents as a damage map for a bare deck.

**Expert Review of Survey Kit**

Before being distributed to respondents, the Survey Kit was sent to 13 engineers for review. The engineers were members of an Expert Task Group (ETG) overseeing Strategic Highway Research Program (SHRP) structures research projects. Changes were made to the Survey Kit to reflect suggestions from the nine ETG members who responded.
3.4.3 Survey Kit Assembly and Distribution

Each Survey Kit was assembled with a unique set of component damage maps, which were chosen randomly to insure that each respondent had an equal chance of evaluating any deck, pier, or abutment. A total of 90 Survey Kits were sent to bridge engineers in the following 25 states identified as using de-icing salts [2:36,2]:

Connecticut  Nebraska
Delaware      New Hampshire
Illinois      New Jersey
Indiana       New York
Iowa          Ohio
Kansas        Pennsylvania
Kentucky      Rhode Island
Maine         Tennessee
Maryland      Vermont
Massachusetts Virginia
Michigan      West Virginia
Minnesota     Wisconsin
Missouri

No Survey Kits were sent to Alaska, since it is a non-contiguous state and was considered to differ significantly from the others in location and climate.

Survey Kits were distributed through SHRP state research coordinators, who were contacted to determine the number of qualified respondents in each state. A qualified respondent was considered to be a bridge engineer who had experience making rehabilitation decisions for concrete bridge components. A total of 60
qualified respondents returned Survey Kits with responses, representing a 67% response rate. At least one Survey Kit with responses was received from every targeted state except Delaware and Massachusetts.
CHAPTER 4: RESULTS AND ANALYSIS

4.1 PRELIMINARY ANALYSIS OF SURVEY RESPONSES

Preliminary analysis of the survey responses consisted of organizing the responses into manageable subdivisions, identifying unqualified respondents, and identifying outlier responses.

4.1.1 Organization of Survey Responses

The survey responses were organized into three types: responses to prediction model support items; responses used to develop prediction models; and responses to miscellaneous items. The most important are the prediction model responses, for which the respondent evaluated a component damage map and made a rehabilitation or treatment recommendation. These responses were used to develop linear regression prediction model equations relating a recommendation response dependent variable to a component damage independent variable.

The support item and miscellaneous item responses consist of all responses not used for building prediction models. The support item responses assisted in determining the approach for developing the prediction models. Miscellaneous item responses are responses to Packet 5 items, which ask the respondent to evaluate the
importance of factors that affect rehabilitation decisions. These responses were analyzed to help provide better understanding of rehabilitation decision logic.

In sections 4.2 (decks) and 4.3 (substructure components), the support item responses are analyzed first, followed by the prediction model responses. The miscellaneous item responses are analyzed in section 4.4. Appendices C, D, and E contain the raw prediction model responses for decks, piers, and abutments, respectively.

4.1.2 Identification of Unqualified Respondents

A total of 63 Survey Kits were returned with responses; however, the responses from three of the Kits were discarded because the respondents were not qualified to participate in the survey. In Survey Kit Packet 5, each respondent was asked to indicate the extent of his or her experience in making rehabilitation decisions. Three respondents indicated that they usually do not have any involvement with rehabilitation decisions, and thus none of their responses were included in the data analysis.

Six respondents had no experience with bare decks, and thus were not qualified to respond to the deck items in Packets 1 through 3. These respondents, who were from Vermont and New Hampshire where most decks have an asphalt
riding surface, completed Packets 4 and 5 only.

4.1.3 Identification of Outlier Responses

Responses from the 60 qualified respondents were examined to detect outliers. An outlier is a response that is considered to be an error (i.e., not a member of the true response population). Outlier responses were identified by internal inconsistencies within an engineer's responses, such as recommending that the Time to Rehabilitate a component is now while recommending repair instead of rehabilitation as the component treatment. Four of the 60 qualified respondents were found to have made outlier responses:

1. Deck and substructure responses were internally inconsistent. The respondent's written comments suggest that he was concerned with component replacement, and thus was unable to relate his recommendations to the rehabilitation point.

2. Responses for a single deck were internally inconsistent. Responses for substructure components indicated that all should have been rehabilitated more than 20 years ago even though none showed severe damage. The respondent may have misunderstood the instructions for
evaluating the substructure components.

3. The respondent recommended the Time to Replace for one deck instead of the Time to Rehabilitate.

4. The respondent recommended the Time to Repair for one deck instead of the Time to Rehabilitate.

In total, 6 of 162 deck TTR responses, 3.7%, were discarded as outliers. Two of 60 substructure packets, 3.3%, were discarded as outliers. Due to the removal of these outlier responses, and to the fact that some of the engineers chose not to respond to individual Survey Kit items, there are items for which less than 60 responses were analyzed.

4.1.4 Validity of Responses Using Snowbelt Standards

The engineers used both Local Standards and Snowbelt Standards to evaluate the component damage maps. Use of Snowbelt Standards required greater estimation by the respondents; therefore, it is reasonable to question the accuracy of their Snowbelt Standards responses. The following question was asked in each Survey Kit to determine how the respondents felt about using Snowbelt Standards:
In general, do you feel comfortable with the answers you provided using Snowbelt Standards? Please circle the number that indicates your response.

YES  1  2  SOMEWHAT  3  4  NO  5

The 59 responses that were obtained are summarized in Table 6. Responses of 1 or 2 are considered to be positive, and responses of 4 or 5 are considered to be negative.

The response given most frequently was for answer choice 2; about a third of the respondents chose this answer. A total of 33 respondents chose either 1 or 2. Thus, approximately 56% of the respondents indicated that they were reasonably comfortable with the answers they provided using Snowbelt Standards. Another 15 respondents (approximately 25%) selected answer choice 3, indicating that they were somewhat comfortable with their answers using Snowbelt Standards. Only 11 of 59 respondents (19%) responded negatively by selecting answer choice 4 or 5.

While it must be acknowledged that some respondents were uncomfortable about using Snowbelt Standards, these respondents were a minority. Since most of the respondents felt at least somewhat comfortable, it is reasonable to conclude that as a whole the Snowbelt Standards responses from the 60 qualified respondents are
valid. Accordingly, the engineers' Snowbelt Standards responses were analyzed along with their Local Standards responses.

### 4.2 ANALYSIS OF SURVEY RESPONSES FOR CONCRETE BRIDGE DECKS

#### 4.2.1 Responses to Support Item for Decks

The support item for decks was as follows:

Assume a bridge deck can be divided into three areas: wheel-path areas in traffic lanes, non-wheel-path areas in traffic lanes, and shoulders.

When rating the overall physical condition of a deck, what is the relative percentage of influence of the physical condition of each area?

<table>
<thead>
<tr>
<th>PHYSICAL CONDITION OF:</th>
<th>% OF INFLUENCE ON &quot;WHOLE DECK&quot; RATING</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Wheel-path areas in traffic lanes</td>
<td>%</td>
</tr>
<tr>
<td>B. Non-wheel-path areas in traffic lanes</td>
<td>%</td>
</tr>
<tr>
<td>C. Shoulders</td>
<td>%</td>
</tr>
</tbody>
</table>

TOTAL = 100 %
The 58 responses to this item are presented in Table 7. There are two approaches which may be used to analyze the responses. First, the mean percentage of influence (PI) gives a general indication of the respondents' opinions. If the physical conditions of the three areas A, B, and C were considered to have approximately equal influence, the mean condition PI for each area would be close to 33.3%. Second, since mean values can be misleading, it is also useful to look at the distribution of the responses, shown in columns 3 through 5 of Table 7. For example, Column 3 shows that 51 of the 58 respondents indicated that the condition PI for deck area A is greater than 33.3%, the equal-influence PI value.

The mean PI values for the condition of areas A, B, and C on the condition rating for the whole deck are 49.1%, 34.6%, and 16.2%, respectively. It is important to note that the mean condition PI for shoulders, 16.2%, is much less than the mean condition PI for both area A and area B.

As shown by the distribution of the responses, most respondents indicated that the wheel-path area condition has a high PI relative to the overall deck condition rating. Fifty-one respondents (88%) indicated that the
Table 7. Summary of 58 responses to item about damage in different deck areas.

<table>
<thead>
<tr>
<th>Area</th>
<th>Mean PI, 58 Resp.</th>
<th># of Resp. PI &gt; 33.3%</th>
<th># of Resp. PI ≈ 33.3%</th>
<th># of Resp. PI &lt; 33.3%</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>49.1%</td>
<td>51</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>B</td>
<td>34.6%</td>
<td>32</td>
<td>6</td>
<td>20</td>
</tr>
<tr>
<td>C</td>
<td>16.2%</td>
<td>0</td>
<td>6</td>
<td>52</td>
</tr>
</tbody>
</table>

Note: PI = percentage of influence.

c-condition PI for wheel-path areas is greater than 33.3%, while only one respondent indicated that condition PI for wheel-path areas is less than 33.3%.

A mixed response is seen for non-wheel-path areas in traffic lanes. Thirty-two respondents indicated that the condition PI for these areas is greater than 33.3%, while 20 respondents indicated that the condition PI for these areas is less than 33.3%.

Addressing shoulder areas, 52 of the 58 respondents (90%) indicated that the condition PI for shoulders is less than 33.3% relative to the overall deck condition rating. Stated simply, 90% of the respondents felt that the physical condition of shoulders has relatively less influence on their whole-deck evaluation than the physical condition of the other deck areas. Notice also that none of the 58 respondents rated the shoulder condition as
having more than 33.3% influence.

In summary, the responses suggest that bridge engineers are most concerned with the physical condition of wheel-path areas when evaluating the overall physical condition of a deck. The condition of non-wheel-path areas in traffic lanes is also considered to be important. There is strong evidence that engineers are least concerned about the physical condition of shoulder areas.

These conclusions suggest that the percentage of surface area damaged for the whole deck may not be the best predictor of an engineer's deck condition evaluation. Since the summation of mean condition PIs for traffic lane areas (areas A and B combined) is 83.7%, a more accurate predictor may be the percentage of surface area damaged in the traffic lanes.

4.2.2 Rehabilitation Prediction Models for Decks

Minitab statistical software [33] and common multiple linear regression techniques [34,35,36,37,38,39] were used to develop linear regression prediction models relating the engineers' deck TTR recommendations to the damage shown on the deck maps.
4.2.2.1 Model-Building Procedure

The model-building procedure outlined in this section was used to develop all prediction models in this study. A model is one or more independent variables that predict a dependent variable [34:401]. For the models in this study, the independent variables are measures of physical damage shown on the component maps, and the dependent variable is either the Time to Rehabilitate or a component treatment recommendation. The model-building procedure consisted of the following steps:

1. The engineers' bridge component recommendation responses were divided into two halves. The first half, Set A, was used to build potential models. The second half, Set B, was used to cross-validate the models from Set A.

2. The Minitab command BREGRESS was used on the Set A responses to determine potential models.

3. The Minitab command REGRESS was used to develop an equation for each potential model.

4. The models were evaluated by comparing several model statistics. The best model was chosen.

5. The cross-validation percentage was determined for the best model. If it was unacceptable, another model was pursued.

6. Using the REGRESS command on the full set of responses, an equation was developed for the best model. The model statistics were checked to confirm the best model for the full data set.

7. Graphic results, including 95% confidence interval lines, were plotted for the best model.
As indicated in steps 1 and 5, each prediction model was subjected to cross-validation, which is a technique for determining whether a model developed from a sample of data is valid for the population of data. A "data-splitting approach" [35:544] was used to cross-validate the models in this study. In step 1, the data were divided into a model-building half and a validating half. In step 5, the cross-validation percentage, which is the percentage of the validating data that fall within prediction intervals developed from the model-building data, was determined. A cross-validation percentage close to 100% is an indication of a successful model.

4.2.2.2 Data-Splitting Approach

There were 156 pairs of TTR responses for decks, each pair consisting of a Local Standards response and a Snowbelt Standards response. To split these 156 pairs, about half of the pairs for each deck were randomly selected. For example, three of the six pairs of responses for survey Deck 1 were taken randomly from the master spreadsheet of responses and placed in a second spreadsheet. This was done for all 18 decks so that two half-size spreadsheets were produced, each having a total of 78 pairs of responses. One of the spreadsheets was
designated as Set A, the other as Set B. The sets of response pairs were halved for each deck, rather than for all of the decks combined, so that each deck would be equally represented by responses in Set A and Set B.

4.2.2.3 Selection of Potential Predictor Variables

The response (dependent) variable for deck models was the recommended Time to Rehabilitate. Thus, potential predictor (independent) variables for the recommended TTR were any information the respondents could have considered when evaluating the decks. The respondents saw the physical damage and physical deck characteristics on the deck maps. In addition, the deck age, AADT, and typical traffic speed were provided for each deck.

To identify potential predictors, it was necessary to account for the way the respondents evaluated the physical damage shown on the maps. Since the deck support item responses indicated that damage in shoulder areas is of relatively less concern than damage in traffic lane areas, it was considered possible that the surface distribution of the deck damage affected the TTR responses. In addition, it is possible that the respondents' evaluations were based in part on the damage type, rather than being based strictly on the percentage
of the deck surface area affected. For example, it is reasonable to suspect that an engineer would react differently to a deck having 10% of its area spalled than to a deck having 10% of its area patched with concrete.

Based on these considerations, potential predictor variables were developed to categorize the observed physical damage. The percentage of area damaged was calculated for three deck regions:

- the whole deck,
- the worst (most damaged) traffic lane, and
- both traffic lanes combined.

For each region, the percentage of area damaged was calculated based on various aggregates of spalls, delaminations, asphalt patches, and concrete patches. The following 20 potential predictor variables were identified:

Basic information shown on deck damage map:

\[ x_1 = \text{surface area of deck (square feet)} \]
\[ x_2 = \% \text{ of whole deck spalled} \]
\[ x_3 = \% \text{ of whole deck delaminated} \]
\[ x_4 = \% \text{ of whole deck patched with asphalt} \]
\[ x_5 = \% \text{ of whole deck patched with concrete} \]
\[ x_6 = \text{lineal feet of cracks / surface area of deck (feet/square feet)} \]
Information provided to respondents:

\[ x_7 = \text{age of deck} \]
\[ x_8 = \text{AADT} \]
\[ x_9 = \text{typical speed of traffic on deck} \]

Total damage for different areas:

\[ x_{10} = \% \text{ of whole deck spalled, delaminated, patched with asphalt, and patched with concrete} \]
\[ x_{11} = \% \text{ of worst traffic lane spalled, delaminated, patched with asphalt, and patched with concrete} \]
\[ x_{12} = \% \text{ of both traffic lanes spalled, delaminated, patched with asphalt, and patched with concrete} \]

Aggregates of damage:

\[ x_{13} = \% \text{ of whole deck spalled and patched with asphalt} \]
\[ x_{14} = \% \text{ of whole deck spalled, delaminated, and patched with asphalt} \]
\[ x_{15} = \% \text{ of worst traffic lane delaminated} \]
\[ x_{16} = \% \text{ of worst traffic lane spalled and patched with asphalt} \]
\[ x_{17} = \% \text{ of worst traffic lane spalled, delaminated, and patched with asphalt} \]
\[ x_{18} = \% \text{ of both traffic lanes delaminated} \]
\[ x_{19} = \% \text{ of both traffic lanes spalled and patched with asphalt} \]
\[ x_{20} = \% \text{ of both traffic lanes spalled, delaminated, and patched with asphalt} \]

These 20 potential predictor variables were used in
the development of both the Snowbelt Standards deck model and the Local Standards deck model.

4.2.2.4 Snowbelt Standards TTR Model for Decks

The BREGRESS command was used on the 78 Snowbelt Standards responses in Set A to evaluate the 20 potential predictor variables. Six of the predictors correlated somewhat with the TTR response variable: $x_8$, $x_{10}$, $x_{14}$, $x_{15}$, $x_{17}$, and $x_{20}$.

Next, the square of each predictor was added as a possible predictor; for example, $x_8^2$ was used in addition to $x_8$. The purpose of adding the square of each predictor was to allow for the possibility of higher-order model terms, which can help account for a curvilinear relationship between the dependent and independent variables.

Using BREGRESS with the six predictors and their squares, three potential models were identified, each consisting of a single predictor and its square term. The power of the higher-order term was adjusted to optimize each model. The optimum models, summarized in Table 8, are based on the following variables:

$$x_{20} = \% \text{ of both traffic lanes spalled, delaminated, and patched with asphalt}$$
Table 8. Potential Snowbelt Standards TTR models for decks.

<table>
<thead>
<tr>
<th>Proposed Model</th>
<th>Regr. P-value</th>
<th>$s$ (yrs.)</th>
<th>$\sum (y_i - \hat{y}_i)^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x_{20}, x_{20.1.1}$</td>
<td>0.000</td>
<td>5.92</td>
<td>3112</td>
</tr>
<tr>
<td>$x_{14}, x_{14.1.1}$</td>
<td>0.000</td>
<td>5.98</td>
<td>3264</td>
</tr>
<tr>
<td>$x_{17}, x_{17.1.1}$</td>
<td>0.000</td>
<td>6.07</td>
<td>2802</td>
</tr>
</tbody>
</table>

$x_{14} = \%$ of whole deck spalled, delaminated, and patched with asphalt

$x_{17} = \%$ of worst traffic lane spalled, delaminated, and patched with asphalt

It is important to note that all three models are based on the same aggregate of damage: spalls, delaminations, and asphalt patches. The predictors based on total damage (i.e., including concrete patches) did not correlate well with the TTR variable.

For all three models, the regression p-value is 0.000, indicating a strong linear relationship between the dependent and independent variables. The regression p-value is the probability that a linear relationship indicated by the sample data does not actually exist for the population data [34:422]. Since this is an error probability, it is desirable for the p-value to be close
to zero.

The three models have approximately equal values of the standard error $s$ of the responses about the regression line. Generally, the model with the lowest standard error value is desirable. In this case, however, the differences in the standard error values are negligible; for all three models, the standard error is approximately 6 years on the TTR scale.

Despite the similarities between the models, some differences are shown by the model statistic presented in Column 4 of Table 8, the error summation $\sum (y_i - \hat{y}_i)^2$ calculated from Set B responses. This summation term, suggested by Ott [35:544], gives a relative indication of how well the model cross-validates. For each potential model, the REGRESS command was used to develop a model equation from the TTR values in Set A. Then, the $x$ values from Set B were put into the Set A model equation, producing fitted TTR values. The squares of the differences between the Set B observed TTR values ($y_i$) and fitted TTR values ($\hat{y}_i$) were then added. The lower the sum-of-squares error, the less lack-of-fit between response sets A and B. The summation term can be used as a means of determining which model cross-validates best relative to the others.
The third model, based on $x_{17}$, was considered to be the best because it had the smallest summation term, approximately 10% lower than the $x_{20}$ model term and 15% lower than the $x_{14}$ model term. The cross-validation percentage was determined for the $x_{17}$ model by developing, for each deck, a prediction interval from the Set A responses. For example, Minitab computed the following prediction interval for future Deck 1 responses $y_i$, based on the Set A Deck 1 responses and the value of $x_{17}$ for Deck 1, 12.5% damage:

$$-11.2 \leq y_i \leq 13.3$$

Of the four Set B Deck 1 responses (-2, 4, 8, and 18), three fall within the Set A prediction interval.

The same method was used on the responses for the other decks. In total, 74 of the 78 Set B deck responses fell within the corresponding Set A prediction intervals. This represents a cross-validation percentage of 94.6%, which was considered to be acceptable for a cross-validation procedure based on 95% prediction intervals.

On the full data set of 156 observations, the $x_{17}$ model produced the following relationship:
\[ \hat{\gamma} = -11.2 + 5.34 \times - 3.41 \times^{1.1} \]  \hspace{1cm} (1)

where

\[ \hat{\gamma} = \text{fitted Time to Rehabilitate for decks, based on Snowbelt Standards.} \]
\[ x = \% \text{ of worst traffic lane spalled, delaminated, and patched with asphalt.} \]

The model is further described by the following information, presented in standard Minitab format:

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Coef</th>
<th>Stdev</th>
<th>t-ratio</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>-11.229</td>
<td>1.586</td>
<td>-7.08</td>
<td>0.000</td>
</tr>
<tr>
<td>x</td>
<td>5.345</td>
<td>1.318</td>
<td>4.06</td>
<td>0.000</td>
</tr>
<tr>
<td>x^{1.1}</td>
<td>-3.4073</td>
<td>0.9123</td>
<td>-3.73</td>
<td>0.000</td>
</tr>
</tbody>
</table>

\[ s = 6.021 \quad R^2 = 31.7\% \quad R^2 \text{ (adj)} = 30.9\% \]

Regression: F computed = 35.59, p = 0.000

The regression p-value, determined from the computed value of the F statistic [34:422], is 0.000 and thus indicates that there is zero probability of falsely assuming a linear relationship between the dependent and independent variables.

For each model coefficient, the t-ratio is used to calculate the coefficient p-value, the error probability that the non-zero coefficient determined from the sample data is actually zero for the population data [34:423]. Since the p-values are 0.000 for the sample coefficients, there is zero probability that the population coefficients
are zero.

The sample coefficient of multiple determination, \( R^2 \) \([34:422,37:272]\), measures the sample data variability that is explained by the regression equation. The population coefficient of multiple determination, adjusted \( R^2 \), is a variability estimate for the full population of data. Since the value of \( R^2 \) is 31.7%, the regression equation for this model explains 31.7% of the variability in the sample data.

Since \( R^2 \) is low, there is too much unexplained variability to conclude that the model equation is a good predictor of future individual TTR responses. However, since the model cross-validates well, 95% confidence intervals based on the model equation can be used to predict future mean TTR responses with 95% certainty \([36:236-40]\).

To illustrate these concepts, two graphs were prepared for the model. Each graph presents TTR as a function of the predictor \( x \). The first graph, Figure 12, shows the model equation line and the responses it is based on. The second graph, Figure 13, shows the 95% confidence interval envelope around the equation line.

Figure 12 shows why \( R^2 \) is low: the data points are spread in a wide band around the equation line. Still, a
Figure 12. Snowbelt Standards TTR responses and model equation line for concrete bridge decks.
Figure 13. Snowbelt Standards TTR model for concrete bridge decks.
general curvilinear relationship can be seen. The relationship is realistic, since low values of x (physical damage) predict negative TTR values, meaning that the deck has not yet reached the rehabilitation time point (TTR = 0). It is important to note that some of the data points on this graph represent more than one observation of the same TTR value, and thus the representation of the data is not completely accurate. Still, the graph gives a general indication of the distribution of the TTR responses.

Figure 13 presents the model equation line and 95% confidence interval lines. The confidence interval envelope widens considerably for x values between 24% and 38%, because there were few responses in this region (see Figure 12). Figure 13 shows that the confidence interval lines intersect the horizontal line TTR = 0 at x values of 9.3% and 13.6%. For worst traffic lane damage values of 9.3% or less, there is at least 95% certainty that the mean TTR response will not be TTR = 0. Similarly, for worst traffic lane damage values of 13.6% or greater, there is at least 95% certainty that the mean TTR response will not be TTR = 0. A mean recommendation by bridge engineers to "rehabilitate the deck now" is probable only for worst traffic lane damage values between 9.3% and
13.6%. Thus, the indicated Snowbelt Standards terminal damage level for decks is $9.3\% < x < 13.6\%$.

4.2.2.5 Local Standards TTR Model for Decks

The model based on the engineers' Local Standards TTR responses was developed using the data-splitting method and 20 predictors described for the Snowbelt Standards model. Using the BREGRESS command, four variables were found to correlate with the Local Standards TTR responses: $x_8$, $x_{14}$, $x_{15}$, and $x_{18}$. Higher-order terms were added and adjusted to optimize the two potential models that are presented in Table 9. The first model is based on a single predictor, $x_{14}$, where:

$$x_{14} = \% \text{ of whole deck spalled, delaminated, and patched with asphalt}$$

The second model is based on the following three predictors:

$$x_8 = \text{AADT}$$

$$x_{12} = \% \text{ of both traffic lanes spalled, delaminated, patched with asphalt, and patched with concrete}$$

$$x_{15} = \% \text{ of worst traffic lane delaminated}$$

Both models seem to be viable. Both have a regression $p$-value of 0.000 using the Set A responses, and
Table 9. Potential Local Standards TTR models for decks.

<table>
<thead>
<tr>
<th>Proposed Model</th>
<th>Response Set A</th>
<th>Response Set B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Regr. P-value</td>
<td>s (yrs.)</td>
</tr>
<tr>
<td>( x_{14}, x_{14}^{1.05} )</td>
<td>0.000</td>
<td>6.65</td>
</tr>
<tr>
<td>( x_8, x_{12}, x_{15} )</td>
<td>0.000</td>
<td>6.70</td>
</tr>
</tbody>
</table>

the standard error (s) values, 6.65 and 6.70 years, are nearly identical. While the error summation value is slightly smaller for the second model, the first model has the practical advantage [37:272] of being based on one predictor rather than three.

The accuracy of both models was assessed using the full set of responses. The p-values for the predictor coefficients were as follows:

<table>
<thead>
<tr>
<th>Predictor</th>
<th>coef.</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>First model:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constant</td>
<td>0.000</td>
<td></td>
</tr>
<tr>
<td>( x_{14} )</td>
<td>0.017</td>
<td></td>
</tr>
<tr>
<td>( x_{14}^{1.05} )</td>
<td>0.023</td>
<td></td>
</tr>
<tr>
<td>Second model:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constant</td>
<td>0.000</td>
<td></td>
</tr>
<tr>
<td>( x_8 )</td>
<td>0.006</td>
<td></td>
</tr>
<tr>
<td>( x_{12} )</td>
<td>0.098</td>
<td></td>
</tr>
<tr>
<td>( x_{15} )</td>
<td>0.002</td>
<td></td>
</tr>
</tbody>
</table>
It is important to note that the coefficient p-value is 0.098 for $x_{12}$ in the second model, indicating a 9.8% probability that the coefficient determined for the sample equation is actually zero for the population equation. While there is considerable disagreement regarding the maximum acceptable p-value, a maximum significance level (probability of error) of 0.05 is common [34:300,37:173, 38:333]. The highest p-value for the first model is 0.023, considerably less than the highest p-value for the second model.

Since it is based on fewer predictors and has more reliable coefficients than the second model, the first model was considered to be the best. The cross-validation percentage calculated for this model was 97.4%, providing strong evidence that the model works well for other data.

On the full data set of 156 observations, the model produced the following relationship:

$$\hat{y} = -10.3 + 14.0 \times 11.4 \times 1.05$$

(2)

where

$\hat{y} = $ fitted Time to Rehabilitate for decks, based on Local Standards.

$x = \%$ of whole deck spalled, delaminated, and patched with asphalt.

Minitab computed the following statistics that describe
the model:

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Coef</th>
<th>Stdev</th>
<th>t-ratio</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>-10.303</td>
<td>1.939</td>
<td>-5.31</td>
<td>0.000</td>
</tr>
<tr>
<td>x</td>
<td>14.014</td>
<td>5.795</td>
<td>2.42</td>
<td>0.017</td>
</tr>
<tr>
<td>x^{1.05}</td>
<td>-11.438</td>
<td>4.979</td>
<td>-2.30</td>
<td>0.023</td>
</tr>
</tbody>
</table>

\[ s = 6.906 \quad R^2 = 22.0\% \quad R^2 (adj) = 21.0\% \]

Regression: \[ F \text{ computed } = 21.59, \quad p = 0.000 \]

All four p-values are close to zero, indicating a dependable model.

The model equation line and 95% confidence interval lines are presented in Figure 14. The confidence interval envelope is slightly wider than the Snowbelt Standards model envelope, reflecting greater variability in the Local Standards responses. The mean TTR = 0 response is probable only for whole-deck damage values between 5.8% and 10.0%. Thus, the indicated Local Standards terminal damage level for decks is 5.8% < x < 10.0%.

4.2.2.6 Comparison of the Deck Models

For the Snowbelt Standards deck model, the predictor is the percentage of the worst traffic lane area that is spalled, delaminated, and patched with asphalt. For the Local Standards deck model, the predictor is the percentage of the whole deck area that is spalled,
Equation Line
95% C.I. for Mean

Figure 14. Local Standards TTR model for concrete bridge decks.
delaminated, and patched with asphalt.

Two important observations can be made about the model predictors. First, the same aggregate of damage is the basis for both predictors; concrete patches are irrelevant to both models. It is reasonable to believe that engineers are concerned about vehicle riding quality and safety when they make deck rehabilitation decisions. Thus, it is realistic for these models to indicate that concrete patches, which are typically sound and smooth, do not have a quantifiable impact on deck rehabilitation decisions relative to spalls, delaminations, and asphalt patches.

A second observation is that the predictor for the Snowbelt Standards model is more specific than the predictor for the Local Standards model. The former is based on damage in the worst traffic lane, while the latter is based on damage on the whole deck. The Snowbelt Standards responses showed a greater consensus of opinion than the Local Standards responses, as indicated by the correlation coefficients for the two models:

- Snowbelt Standards deck model: \( R^2 = 31.7\% \)
- Local Standards deck model: \( R^2 = 22.0\% \)

It is consistent, then, that the Snowbelt Standards model is based on a more specific predictor. In addition, the
Snowbelt Standards model predictor is consistent with the deck support item responses, which indicate that the condition of non-traffic-lane areas is of relatively less concern than the condition of traffic-lane areas.

In summary, both models are considered to be valid for predicting mean TTR responses for concrete bridge decks. One model predicts recommended rehabilitation practices, while the other predicts current rehabilitation practices.

4.2.2.7 Limitations of the Deck Models

Both models are based on engineers' evaluations of 18 damage maps for decks that:

- carry two lanes of traffic, and
- have surface areas ranging from approximately 3900 to 9300 square feet.

The deck models presented may be less applicable to decks having other than two lanes of traffic or having surface areas greater than approximately 9300 square feet. Single-lane deck rehabilitation may require bridge closure and traffic detours, while rehabilitation for decks having more than two lanes may require additional lane changes. The rehabilitation labor and materials costs are likely to be greater for decks having surface areas exceeding the
surface areas of the decks in this study. Thus, for decks outside the scope of this study, potentially greater rehabilitation costs may correspond to greater terminal damage levels.

4.3 ANALYSIS OF SURVEY RESPONSES FOR CONCRETE BRIDGE SUBSTRUCTURE COMPONENTS

4.3.1 Responses to Support Item for Substructure Components

During the field study, it was observed that most of the 18 bridges showed relatively less physical damage on the substructure components than on the deck. This is not surprising, because substructure components are exposed to less salt-laden water than decks and are not subjected to surface traffic loads. Based on the observed component damage disparities, it was hypothesized that the decision to repair or rehabilitate substructure components often depends on whether a decision has been made to repair or rehabilitate the deck. The following item was included in each Survey Kit to test this hypothesis:

Of the substructures rehabilitated or repaired in your engineering district, for what percentage is this statement true:
"The decision to repair or rehabilitate substructure components is significantly affected by whether a decision has been made to repair or rehabilitate the deck."

For substructure components, we define rehabilitation as REMOVAL OF UNSOUND CONCRETE, PATCHING, AND PARTIAL OR COMPLETE ENCASEMENT OF THE COMPONENT.

Please circle the letter of the choice that completes your response: "The statement above is true for about ____ of the substructures rehabilitated."

A. 100%   G. 40%  
B. 90%   H. 30%  
C. 80%   I. 20%  
D. 70%   J. 10%  
E. 60%   K. 0%  
F. 50%

The 60 responses to this item are presented in Table 10. Forty-six of the responses are for answer choices 60% to 100%. Thus, 77% of the respondents indicated that the statement is true for 60% or more of the substructures rehabilitated.

The responses to this item support the hypothesis that the decision to repair or rehabilitate substructure components often depends on whether a decision has been made to repair or rehabilitate the deck. This conclusion suggests that the physical damage level may not be the primary basis for substructure component rehabilitation decisions. The hypothesis was explored further by developing rehabilitation prediction models from the
Table 10. Summary of 60 responses to item about the influence of deck rehabilitation decisions on substructure component rehabilitation decisions.

<table>
<thead>
<tr>
<th>Answer Choices: Percentage of Substructures Rehabilitated</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 90 80 70 60 50 40 30 20 10 0</td>
</tr>
<tr>
<td># of Resp. 6 19 11 7 3 1 0 4 3 3 3</td>
</tr>
</tbody>
</table>

responses for substructure components. The responses supported five workable models for piers, and no workable models for abutments.

4.3.2 Rehabilitation Prediction Models for Piers

Each respondent evaluated two of the eleven piers included in the survey. The engineers gave three types of responses for each pier they evaluated:

1. The Time to Rehabilitate.

2. A treatment recommendation of what work should be done to the pier now, given its condition and assuming no deck work will be done in the near future. The treatment choices were do nothing, repair, or rehabilitate.

3. A treatment recommendation of what work should be done to the pier now, assuming a decision has already been made to rehabilitate the deck.

Since two responses (Snowbelt Standards and Local Standards) were given for each response type, six
prediction models were attempted.

The 116 sets of pier responses were divided into sets A and B, each having 58 sets of responses. As done for decks, the Set A responses were used to build the models and the Set B responses were used to cross-validate the models.

4.3.2.1 Selection of Potential Predictor Variables

The pier damage maps showed three deterioration indicators: spalls, cracks, and patches. Only two of the eleven piers had more than one patched area; thus, an aggregate of spalls and cracks was considered to be a more likely predictor than an aggregate of all three indicators. Since cracks are expressed in lineal feet, not square feet, an aggregate of "percentage of area cracked and spalled" could not be determined directly. However, it was considered likely that engineers view cracks as an indication of an area of unsound concrete. During the field study, it was observed for both decks and columns that the concrete within several inches of a crack was often delaminated. Based on this observation, the total lineal feet of cracking for each pier was multiplied by an equivalent damage width \([40:44]\) to yield an equivalent area of unsound concrete as indicated by
cracks. An aggregate quantity, the percentage of pier area spalled and having unsound concrete as indicated by cracks, was then calculated for each pier.

The selected equivalent damage width was four inches. Since a common cover depth of concrete over reinforcement is two inches, a crack due to corrosion must propagate approximately two inches to reach the concrete surface. If a crack has propagated to the concrete surface, it is reasonable to suspect that the concrete within two inches of the bar on either side is delaminated already or will delaminate in the near future.

The potential predictors determined for pier models are listed below. The pier area is the summation of areas of all column and pier cap surfaces, with the exception of the horizontal top surface of the pier cap.

Basic information shown on pier damage map:

\[ x_1 = \text{Surface area of pier (square feet)} \]
\[ x_2 = \% \text{ of pier area spalled} \]
\[ x_3 = \text{Lineal feet of cracks per square foot of pier area} \]
\[ x_4 = \% \text{ of pier area patched} \]

Information provided to respondents:

\[ x_5 = \text{age of pier} \]
Aggregates of damage:

\[ x_6 = \% \text{ of pier area spalled and having unsound concrete as indicated by cracks} \]

\[ x_7 = \% \text{ of pier area spalled, patched, and having unsound concrete as indicated by cracks} \]

Five pier models were developed using the model-building procedure described for decks. All five pier models were based on a single predictor, \( x_6 \). None of the models were significantly improved by the addition of a second predictor or higher-order terms.

4.3.2.2 Attempted Snowbelt Standards TTR Model for Piers

Two Snowbelt Standards models developed from the Set A responses seemed feasible, one based on \( x_6 \) and the other based on \( x_4 \) and \( x_6 \). However, both models were found to be unacceptable using the full data set. For the model based on \( x_6 \), the cross-validation percentage (83.3%) was much less than the desired 95% and was thus considered to be unacceptable. For the two-predictor model, the high coefficient p-value for \( x_4 \) (0.119) was considered to be unacceptable. Thus, no Snowbelt Standards TTR models for piers were developed.
4.3.2.3 Local Standards TTR Model for Piers

The best model on the Set A data was based on $x_6$. The cross-validation percentage (92.6%) was slightly less than 95% but was thought to indicate a marginally acceptable model.

On the full data set, a total of 113 observations, the model produced the following relationship:

$$\hat{y} = -18.8 + 3.35 x$$  \hspace{1cm} (3)

where

$$\hat{y} = \text{fitted Time to Rehabilitate for piers, based on Local Standards.}$$

$$x = \% \text{ of pier area spalled and having unsound concrete as indicated by cracks}$$

The model statistics are as follows:

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Coef</th>
<th>Stdev</th>
<th>t-ratio</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>-18.792</td>
<td>1.998</td>
<td>-9.41</td>
<td>0.000</td>
</tr>
<tr>
<td>$x$</td>
<td>3.347</td>
<td>1.004</td>
<td>3.33</td>
<td>0.001</td>
</tr>
</tbody>
</table>

$s = 10.52$ \hspace{1cm} $R^2 = 9.1\%$ \hspace{1cm} $R^2$ (adj) = 8.3%

Regression: F computed = 11.11, \hspace{0.5cm} p = 0.001

All three p-values are sufficiently close to zero. The standard error (s) value, 10.52 years on the TTR scale, is considerably greater than the standard error values for the deck models, which were between 6 and 7 years. The considerable variability in the model responses is further
indicated by the low correlation coefficients.

The equation line and 95% confidence interval lines for the model are shown in Figure 15. The model boundaries indicate that none of the eleven survey piers have reached the rehabilitation point. It is only by extrapolation that the upper confidence interval line intersects the horizontal line TTR = 0. Since the intersection point occurs for an $x$ value of 4.1%, there is at least 95% certainty that the mean TTR response will not be TTR = 0 for $x$ values of 4.1% or less. Thus, only a one-sided terminal damage level for piers is suggested by this model. The pier damage maps produced from the 18 study bridges did not show enough physical damage to allow development of a complete terminal damage level for piers.

4.3.2.4 Limitations of the Pier Model

The model is based on evaluations of damage maps for eleven open-type piers having either three or four columns. The piers range in surface area from about 700 to 900 square feet. The model may not be applicable to other types of piers, such as hammerhead piers, for which the rehabilitation approach may be different. In addition, the model may be less applicable to piers that have surface areas greater than the survey pier surface
Figure 15. Local Standards TTR model for concrete bridge piers.
areas, because piers having greater surface areas may be more costly to rehabilitate.

4.3.2.5 Treatment Recommendation Models for Piers

In addition to making TTR recommendations, the respondents recommended one of the following three treatments for each pier they evaluated:

A. Do nothing.

B. Repair: patch damaged areas.

C. Rehabilitate: remove unsound concrete, patch, and encase.

The four models discussed in the next sections are based on the respondents' treatment recommendations. To facilitate regression analysis, the engineers' responses (A, B, or C) were converted to numbers: 0 for do nothing, 1 for repair, and 2 for rehabilitate.

For each pier they evaluated, the respondents provided two treatment recommendations, each based on a different assumption. One pier treatment recommendation was made based on the assumption that the bridge deck would not be rehabilitated in the near future. The other pier treatment recommendation was made based on the assumption that a decision has been made to rehabilitate the deck.
4.3.2.6 Snowbelt Standards Treatment Recommendation

Models for Piers

The model based on the assumption that the deck would not be rehabilitated is presented first. The best model, \( x_6 \), yielded an acceptable cross-validation percentage of 94.4%. The following model equation and statistics were developed from the full data set of 110 responses:

\[
\hat{y} = 0.193 + 0.132 x \tag{4}
\]

where

\[ \hat{y} = \text{fitted pier treatment recommendation, based on Snowbelt Standards and assuming the deck will not be rehabilitated in the near future.} \]

\[ x = \% \text{ of pier area spalled and having unsound concrete as indicated by cracks.} \]

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Coef</th>
<th>Stdev</th>
<th>t-ratio</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>0.1926</td>
<td>0.1143</td>
<td>1.68</td>
<td>0.095</td>
</tr>
<tr>
<td>( x )</td>
<td>0.13177</td>
<td>0.05782</td>
<td>2.28</td>
<td>0.025</td>
</tr>
</tbody>
</table>

\[ s = 0.6001 \quad R^2 = 4.6\% \quad R^2 \text{ (adj) } = 3.7\% \]

Regression: \( F \text{ computed } = 5.19, \quad p = 0.025 \)

The standard error value, \( s = 0.6001 \), is consistent with treatment responses ranging from 0 to 2. The regression and \( x \) p-values are sufficiently low. The constant p-value, 0.095, is greater than 0.05 and thus casts doubt on the validity of the constant.
Next, a model based on the assumption that a decision has been made to rehabilitate the deck was developed. For the best model, again $x_6$, the cross-validation percentage was 96.6%. The full data set of 116 responses produced the following model equation and statistics:

$$\hat{y} = 0.630 + 0.135 x$$  (5)

where

$\hat{y} =$ fitted pier treatment recommendation, based on Snowbelt Standards and assuming a decision has been made to rehabilitate the deck.

$x =$ $\%$ of pier area spalled and having unsound concrete as indicated by cracks.

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Coef</th>
<th>Stdev</th>
<th>t-ratio</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>0.6302</td>
<td>0.1110</td>
<td>5.68</td>
<td>0.000</td>
</tr>
<tr>
<td>$x$</td>
<td>0.13483</td>
<td>0.05611</td>
<td>2.40</td>
<td>0.018</td>
</tr>
</tbody>
</table>

$s = 0.5907 \quad R^2 = 4.8\% \quad R^2 (adj) = 4.0\%$

Regression: $F$ computed $= 5.77, \quad p = 0.018$

All three p-values are close to zero. The standard error value, $s = 0.59$, is nearly identical to the standard error value of 0.60 for the model assuming no deck rehabilitation.

Both Snowbelt Standards treatment recommendation models are presented in Figure 16. The y-axis of the graph can be interpreted as follows. While the actual
Figure 16. Snowbelt Standards treatment recommendation models for concrete bridge piers.
responses are based on a discrete scale of 0, 1, and 2, the regression model equations are continuous on the y-axis. It is therefore appropriate to define the following ranges on the y-axis:

\[
\begin{align*}
0.0 \leq y \leq 0.5: & \quad \text{Do nothing} \\
0.5 < y < 1.5: & \quad \text{Repair} \\
1.5 \leq y \leq 2.0: & \quad \text{Rehabilitate}
\end{align*}
\]

Since these ranges are approximations, and the model assuming no deck rehabilitation has a questionable model constant, no dependable quantitative conclusions can be drawn from these models. However, two dependable qualitative conclusions are indicated. First, the 95% confidence interval envelope for the model assuming deck rehabilitation is displaced upward compared to the envelope for the other model, indicating that it is more likely for a pier to be repaired or rehabilitated if a decision has already been made to rehabilitate the deck. Second, nearly the entire envelope for the model assuming deck rehabilitation is within the repair range, suggesting that if a decision has been made to rehabilitate the deck, it is likely that any pier damage will be repaired.
4.3.2.7 Local Standards Treatment Recommendation Models for Piers

For both of the Local Standards pier treatment recommendation models that were developed, the best predictor was $x_6$ and the cross-validation percentages were acceptable: 96.4% for the model assuming no deck rehabilitation, and 94.8% for the model assuming a decision has been made to rehabilitate the deck.

Based on 112 responses, the model assuming no deck rehabilitation is:

$$\hat{Y} = 0.026 + 0.177x$$

(6)

where

$$\hat{Y} = \text{fitted pier treatment recommendation, based on Local Standards and assuming the deck will not be rehabilitated in the near future.}$$

$$x = \% \text{ of pier area spalled and having unsound concrete as indicated by cracks.}$$

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Coef</th>
<th>Stdev</th>
<th>t-ratio</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>0.0262</td>
<td>0.1013</td>
<td>0.26</td>
<td>0.797</td>
</tr>
<tr>
<td>$x$</td>
<td>0.17702</td>
<td>0.05115</td>
<td>3.46</td>
<td>0.001</td>
</tr>
</tbody>
</table>

$s = 0.5340 \quad R^2 = 9.8\% \quad R^2 (adj) = 9.0\%$

Regression: $F$ computed = 11.98, $p = 0.001$

The regression and $x$ p-values are very close to zero. While the p-value for the equation constant is 0.797, the
value of the constant (0.0262) is so close to zero that it has no significant effect on the model equation.

Based on 116 responses, the model assuming that a decision has been made to rehabilitate deck is:

\[ \hat{y} = 0.665 + 0.125 x \]  

(7)

where

\[ \hat{y} = \text{fitted pier treatment recommendation, based on Local Standards and assuming a decision has been made to rehabilitate the deck.} \]

\[ x = \% \text{ of pier area spalled and having unsound concrete as indicated by cracks.} \]

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Coef</th>
<th>Stdev</th>
<th>t-ratio</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>0.6648</td>
<td>0.1121</td>
<td>5.93</td>
<td>0.000</td>
</tr>
<tr>
<td>x</td>
<td>0.12475</td>
<td>0.05668</td>
<td>2.20</td>
<td>0.030</td>
</tr>
</tbody>
</table>

\[ s = 0.5967 \quad R^2 = 4.1\% \quad R^2 \text{ (adj)} = 3.2\% \]

Regression: F computed = 4.84, p = 0.030

All three p-values are acceptable.

Both models are presented in Figure 17. Once again, the confidence interval envelope for the model assuming deck rehabilitation is displaced upward relative to the envelope for the other model. The models appear to be nearly identical to the Snowbelt Standards models presented in Figure 16.
Figure 17. Local Standards treatment recommendation models for concrete bridge piers.
4.3.2.8 Conclusions from the Pier Treatment Recommendation Models

The Local Standards and Snowbelt Standards pier treatment recommendation models support the qualitative conclusion that pier repair or rehabilitation is more likely to occur if a decision has been made to rehabilitate the deck. Thus, the models are consistent with the responses to the substructure component support item.

4.3.3 Attempted Rehabilitation Prediction Models for Abutments

Each respondent evaluated one of the six abutments that were included in the survey. The data-splitting approach was used to divide the 58 sets of abutment responses into half-size data sets A and B. Model selection was done using the Minitab BREGRESS command on the Set A data as described previously.

As described for piers, there were three types of responses elicited for abutments: the Time to Rehabilitate, and two separate treatment recommendations. Since two responses (Snowbelt Standards and Local Standards) were given for each response type, six models were attempted.
4.3.3.1 Selection of Potential Predictor Variables

Five of the six abutments showed only one type of damage: cracks. Since only one abutment showed a spalled area, the percentage of surface area spalled could not be a potential predictor of the engineers' abutment responses. Thus, cracks were considered to be the only damage-based source of potential predictors. For piers, the lineal feet of cracking had been converted to an equivalent area of unsound concrete so that cracks and spalls could be aggregated. For abutments, however, there was no need to aggregate cracks and spalls, and thus the extent of cracking was calculated as lineal feet of cracks per square foot of abutment surface area.

Four of the abutments showed vertical cracks, which appeared to have been caused by shrinkage and expansion of the abutment rather than by steel reinforcement corrosion, since corrosion-induced cracks on abutments are usually horizontal or semi-circular. To account for the possibility that the respondents reacted primarily to the non-vertical cracks on the damage maps, the extent of non-vertical cracking (lineal feet of non-vertical cracks per square foot of abutment surface area) was also calculated.

The following four potential abutment model predictors were identified:
\[ x_1 = \text{surface area of abutment (square feet)} \]
\[ x_2 = \text{lineal feet of all cracks per square foot of abutment area} \]
\[ x_3 = \text{lineal feet of non-vertical cracks per square foot of abutment area} \]
\[ x_4 = \text{age of abutment} \]

For all six attempted models, no correlation was found between the engineers' responses and the potential predictors.

4.3.3.2 Efforts to Develop Prediction Models for Abutments

The best of the attempted abutment models are presented in Table 11. The regression p-values, which range from 0.177 to 0.752, are all much greater than 0.05 and thus are unacceptable.

4.3.3.3 Conclusions for Abutments

The survey responses did not support any models to predict the Time to Rehabilitate, or treatment recommendations, for abutments. The attempted models may have failed in part because most of the six survey abutments showed little damage. For example, since the respondents evaluated some mildly damaged abutments, many of their TTR recommendations were based on vague estimates.
Table 11. Attempted rehabilitation prediction models for abutments.

<table>
<thead>
<tr>
<th>Abutment Prediction Model Attempted</th>
<th>Full Data Set</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&quot;Best&quot; Pred.</td>
<td>Regr. p-value</td>
</tr>
<tr>
<td>TTR, Snowbelt Standards</td>
<td>$x_2$</td>
<td>0.752</td>
</tr>
<tr>
<td>TTR, Local Standards</td>
<td>$x_2$</td>
<td>0.291</td>
</tr>
<tr>
<td>Treatment, deck not rehab., Snowbelt Stds.</td>
<td>$x_3$</td>
<td>0.237</td>
</tr>
<tr>
<td>Treatment, deck being rehab., Snowbelt Stds.</td>
<td>$x_2$, $x_4$</td>
<td>0.198</td>
</tr>
<tr>
<td>Treatment, deck not rehab., Local Stds.</td>
<td>$x_1$, $x_2$, $x_4$</td>
<td>0.177</td>
</tr>
<tr>
<td>Treatment, deck being rehab., Local Stds.</td>
<td>$x_3$</td>
<td>0.360</td>
</tr>
</tbody>
</table>

of the abutment condition in the distant future. Twelve of the 56 Local Standards TTR responses for abutments (21%) were "it will be more than 20 years before this component should be rehabilitated." For analysis, these responses were converted to "-30 years" as a reasonable interpretation of "more than 20 years" on the TTR scale. It is likely that the relatively high percentage of -30 TTR responses limited the possibility of correlation between the response and predictor variables.

The treatment recommendation models, however, should not have been affected by the lack of heavily damaged
survey abutments as much as the TTR models. Since treatment recommendations are for work to be done now, there is no need to estimate the future physical condition of the component. Still, no acceptable treatment recommendation models were developed, which suggests that terminal damage levels for abutments may be difficult, or impossible, to quantify. Based on the substructure support item responses, it is likely that abutment rehabilitation decisions are highly dependent on deck rehabilitation decisions.

4.4 ANALYSIS OF SURVEY RESPONSES TO MISCELLANEOUS ITEMS

In Packet 5 of each Survey Kit, the engineers were asked to respond to the following general items about rehabilitation practices. Only qualitative conclusions can be made from the responses to these items.

4.4.1 Factors that Affect Deck Rehabilitation Decisions

The purpose of this item was to determine how and why engineers decide to rehabilitate a bridge deck.

Assume you are trying to decide whether a bridge deck should be rehabilitated. You are considering several factors carefully before making your decision. Some factors that might affect your decision are listed below.
At the bottom of the list, please write in any other factors that you might consider before making your decision.

Then, choose from the whole list the six factors that you think most strongly influence this decision. Circle the letter of each factor.

In the right column, rank the chosen factors from 1 to 6, with 1 meaning the most influence.

<table>
<thead>
<tr>
<th>FACTOR AFFECTING DECISION</th>
<th>INFLUENCE OF FACTOR ON DECISION</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Availability of funds/labor</td>
<td>___</td>
</tr>
<tr>
<td>B. Amount of physical deterioration</td>
<td>___</td>
</tr>
<tr>
<td>C. Distribution of physical deterioration</td>
<td>___</td>
</tr>
<tr>
<td>D. Degree of roughness of riding surface</td>
<td>___</td>
</tr>
<tr>
<td>E. Typical speed of traffic</td>
<td>___</td>
</tr>
<tr>
<td>F. Volume of traffic (AADT)</td>
<td>___</td>
</tr>
<tr>
<td>G. Public opinion</td>
<td>___</td>
</tr>
<tr>
<td>H. Aesthetic appearance</td>
<td>___</td>
</tr>
<tr>
<td>I. Need for other work along same roadway</td>
<td>___</td>
</tr>
<tr>
<td>J. Availability of a detour for traffic</td>
<td>___</td>
</tr>
<tr>
<td>K. Need for work on other bridges in area</td>
<td>___</td>
</tr>
<tr>
<td>L. Condition of superstructure</td>
<td>___</td>
</tr>
<tr>
<td>M. Condition of substructure</td>
<td>___</td>
</tr>
<tr>
<td>N. Need to modify appurtenances: parapets, guard rails, drainage system, etc.</td>
<td>___</td>
</tr>
<tr>
<td>O. Total surface area of deck</td>
<td>___</td>
</tr>
<tr>
<td>P. Rate of physical deterioration</td>
<td>___</td>
</tr>
<tr>
<td>Q. ________________________________</td>
<td>___</td>
</tr>
<tr>
<td>R. ________________________________</td>
<td>___</td>
</tr>
<tr>
<td>S. ________________________________</td>
<td>___</td>
</tr>
<tr>
<td>T. ________________________________</td>
<td>___</td>
</tr>
</tbody>
</table>

The respondents were asked to choose six factors, and then rank them from 1 to 6. Since all 60 engineers provided answers, a total of 360 rank responses were obtained. These responses are presented in Table 12, which shows, for example, that 15 respondents ranked factor A as being
Table 12. Summary of rank responses for factors that affect deck rehabilitation decisions.

<table>
<thead>
<tr>
<th>Factor</th>
<th>No. of Resp. who Ranked the Factor:</th>
<th>Total Resp.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>A</td>
<td>15</td>
<td>6</td>
</tr>
<tr>
<td>B</td>
<td>31</td>
<td>12</td>
</tr>
<tr>
<td>C</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td>D</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>E</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>F</td>
<td>0</td>
<td>8</td>
</tr>
<tr>
<td>G</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>H</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>I</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>J</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>K</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>L</td>
<td>4</td>
<td>11</td>
</tr>
<tr>
<td>M</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>N</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>O</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>P</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>Q-T</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Σ=360
number one in influence.

The far right column of Table 12 gives the total number of respondents who selected the factor as being one of the six most influential. For example, 46 of the 60 respondents included factor A among the six factors they chose. This column shows that each of factors A, B, F, L, and P were selected by at least half of the respondents. Since these were the most frequently selected factors, they are indicated as being the most influential factors on the list.

Table 13 lists the five factors in the order of selection frequency, as suggested by the aggregates of rank responses shown in columns 2 through 4. For example, factor B was ranked number 1 by 31 respondents; number 1 or 2 by 43 respondents; number 1, 2, or 3 by 49 respondents; and so on. The rank response aggregate values show the same numerical order in each column.

Based on the information in Table 13, the five deck rehabilitation decision factors most frequently selected as being influential are as follows, listed in the order of selection frequency:

1. Amount of physical deterioration
2. Availability of funds/labor
3. Condition of the superstructure
Table 13. The five deck rehabilitation decision factors most frequently selected as being influential, listed in the order of selection frequency.

<table>
<thead>
<tr>
<th>Factor</th>
<th>No. of Resp. Who Ranked the Factor:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>B</td>
<td>31</td>
</tr>
<tr>
<td>A</td>
<td>15</td>
</tr>
<tr>
<td>L</td>
<td>4</td>
</tr>
<tr>
<td>F</td>
<td>0</td>
</tr>
<tr>
<td>P</td>
<td>0</td>
</tr>
</tbody>
</table>

4. Volume of traffic (AADT)

5. Rate of physical deterioration

The factor most frequently selected as being influential is the amount of physical deterioration on the deck. This finding supports the validity of the deck rehabilitation prediction models, which predict the Time to Rehabilitate based on the magnitude of a physical deterioration parameter. Still, it is important to note that the second factor on the list is the availability of funds and labor. Clearly, decisions about deck rehabilitation are strongly affected by economic considerations.

The remaining factors frequently selected as being influential are the condition of the superstructure, the traffic volume (AADT), and the rate of physical deterioration. The substructure condition is not among
the five deck rehabilitation decision factors most frequently selected as being influential.

4.4.2 Influence of Substructure Component Rehabilitation Decisions on Deck Rehabilitation Decisions

As discussed previously, survey responses from this study suggest that substructure component rehabilitation decisions are often significantly affected by deck rehabilitation decisions. The following item was included in the survey to determine if the opposite is true:

Of the decks rehabilitated in your engineering district, for what percentage is this statement true:

"The decision to repair or rehabilitate the deck is significantly affected by whether a decision has been made to repair or rehabilitate substructure components."

For decks, we define rehabilitation as REMOVAL OF UNSOUND CONCRETE, PATCHING, AND OVERLAY.

Please circle the letter of the choice that completes your response: "The statement is true for about _____ of the decks rehabilitated."

A. 100%  G. 40%
B. 90%  H. 30%
C. 80%  I. 20%
D. 70%  J. 10%
E. 60%  K. 0%
F. 50%

The 59 responses to this item are summarized in Table 14. Forty-nine of the respondents (83%) indicated that the
Table 14. Summary of 59 responses to item about the influence of substructure component rehabilitation decisions on deck rehabilitation decisions.

<table>
<thead>
<tr>
<th>Answer Choices: % of decks rehabilitated</th>
<th># of Res.</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>90</td>
<td>1</td>
</tr>
<tr>
<td>80</td>
<td>1</td>
</tr>
<tr>
<td>70</td>
<td>0</td>
</tr>
<tr>
<td>60</td>
<td>0</td>
</tr>
<tr>
<td>50</td>
<td>1</td>
</tr>
<tr>
<td>40</td>
<td>1</td>
</tr>
<tr>
<td>30</td>
<td>1</td>
</tr>
<tr>
<td>20</td>
<td>5</td>
</tr>
<tr>
<td>10</td>
<td>26</td>
</tr>
<tr>
<td>0</td>
<td>23</td>
</tr>
</tbody>
</table>

The statement is true for 10% or less of the decks rehabilitated. Only five respondents (8%) indicated that the statement is true for 30% or more of the decks rehabilitated. The responses strongly suggest that decisions to repair or rehabilitate a concrete bridge deck are usually not significantly affected by whether a decision has been made to repair or rehabilitate the substructure components.

4.4.3 Influence of Bridge Part Conditions on the Overall Bridge Condition Rating

Assume a bridge is classified as three parts: deck, superstructure, and substructure.

Assume you are asked to rate the overall physical condition of the bridge as a whole. To do this, you first assess the physical condition of each bridge part.
When rating the physical condition of the "whole bridge", what is the relative percentage of influence of the physical condition of the deck, superstructure, and substructure?

<table>
<thead>
<tr>
<th>PHYSICAL CONDITION OF:</th>
<th>% OF INFLUENCE ON &quot;WHOLE BRIDGE&quot; RATING</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Deck</td>
<td>%</td>
</tr>
<tr>
<td>B. Superstructure</td>
<td>%</td>
</tr>
<tr>
<td>C. Substructure</td>
<td>%</td>
</tr>
</tbody>
</table>

TOTAL = 100 %

The 59 responses to this item are summarized in Table 15, which shows that the mean condition percentage of influence is approximately equal for decks and substructures. The mean condition PI for superstructures, 39.8%, is slightly greater than the mean condition PIs for decks and substructures.

The relative influence of each bridge part condition is further indicated by the distribution of the responses, summarized in Columns 3 through 5 of Table 15. Approximately two-thirds of the respondents indicated that the mean condition PI for superstructures is greater than 33%. For both decks and substructures, only one-third of the respondents indicated that the mean condition PI is greater than 33%. The responses suggest that a majority of engineers think the physical condition of the superstructure influences the overall bridge condition.
Table 15. Summary of 59 responses to item about the influence of bridge part conditions on the overall bridge condition rating.

<table>
<thead>
<tr>
<th>Bridge Part</th>
<th>Mean PI</th>
<th># of Resp.</th>
<th># of Resp.</th>
<th># of Resp.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>PI &gt; 33.3%</td>
<td>PI ≈ 33.3%</td>
<td>PI &lt; 33.3%</td>
</tr>
<tr>
<td>Deck</td>
<td>29.4</td>
<td>20</td>
<td>4</td>
<td>35</td>
</tr>
<tr>
<td>Superstr.</td>
<td>39.8</td>
<td>39</td>
<td>5</td>
<td>15</td>
</tr>
<tr>
<td>Substr.</td>
<td>30.8</td>
<td>19</td>
<td>4</td>
<td>36</td>
</tr>
</tbody>
</table>

Note: PI = percentage of influence.

rating slightly more than the condition of either the deck or the substructure. Although superstructures were not addressed in this study, it is important to acknowledge that they are significant in the bridge rehabilitation process.

4.4.4 Relative Importance of Bridge Component Information Provided to Respondents

For the decks in this survey, you were provided with the four pieces of information listed below.

When deciding the Time to Rehabilitate for each deck, what was the relative percentage of influence of each piece of information?
The mean percentages of influence determined from the 53 sets of responses are summarized in Table 16. The mean PI for "deterioration shown on map" (60.4%) is greater than the summation of the mean PIs for the other three pieces of information. Regarding the distribution of the responses, 51 of the 53 respondents (96%) indicated that "deterioration" had the greatest percentage of influence on their deck TTR responses. Of the two respondents who did not give "deterioration" the greatest PI, one indicated that "age" had the greatest PI, while the other indicated that "deterioration" and "age" had the same PI. The responses suggest that nearly all of the survey engineers based their deck rehabilitation responses primarily on the deterioration shown on the deck damage maps.

Responses to the following item suggest a similar conclusion regarding the engineers' substructure component rehabilitation responses:
Table 16. Summary of 53 sets of responses to item about the relative influence of deck information on deck rehabilitation recommendations.

<table>
<thead>
<tr>
<th>Piece of Information</th>
<th>Percentage of Influence</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
</tr>
<tr>
<td>Age of deck</td>
<td>19.7</td>
</tr>
<tr>
<td>Deterioration shown on map</td>
<td>60.4</td>
</tr>
<tr>
<td>AADT</td>
<td>13.7</td>
</tr>
<tr>
<td>Typical speed of traffic</td>
<td>6.2</td>
</tr>
</tbody>
</table>

For the substructure components in this survey, you were provided with the two pieces of information listed below.

When deciding the Time to Rehabilitate for each substructure component, what was the relative percentage of influence of each piece of information?

% OF INFLUENCE ON "TIME TO REHABILITATE"

<table>
<thead>
<tr>
<th>PIECE OF INFORMATION</th>
<th>% OF INFLUENCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Age of substructure component</td>
<td>____ %</td>
</tr>
<tr>
<td>B. Deterioration shown on map</td>
<td>____ %</td>
</tr>
<tr>
<td>TOTAL = 100 %</td>
<td></td>
</tr>
</tbody>
</table>

The mean percentages of influence determined from the 59 sets of responses are summarized in Table 17. The mean PI for "deterioration" is 76.9%, three times the mean PI for "age". Fifty-two respondents (88%) indicated that "deterioration" had a greater percentage of influence on their TTR recommendations than "age", while only three
Table 17. Summary of 59 sets of responses to item about the relative influence of substructure component information on substructure component rehabilitation recommendations.

<table>
<thead>
<tr>
<th>Piece of Information</th>
<th>Percentage of Influence</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
</tr>
<tr>
<td>Age of substructure comp.</td>
<td>23.1</td>
</tr>
<tr>
<td>Deterioration shown on map</td>
<td>76.9</td>
</tr>
</tbody>
</table>

respondents indicated that "age" had the greater PI. The remaining four respondents indicated that "deterioration" and "age" had the same PI.

The responses to these two survey items simply indicate that most of the respondents based their bridge component rehabilitation recommendations primarily on the deterioration shown on the component damage maps. This conclusion is consistent with the rehabilitation prediction models developed in this study, since all of the models relate a rehabilitation recommendation variable to the magnitude of a physical deterioration parameter.
CHAPTER 5: FINDINGS AND CONCLUSIONS

The study findings and conclusions presented in this chapter are based on opinion survey responses from 60 bridge engineers. Due to the specific scope of the opinion survey, the findings and conclusions are applicable only to bare reinforced concrete bridge components that deteriorate as a result of corrosion of the reinforcing steel, induced by exposure to chloride de-icing salts.

5.1 FINDINGS

1. A majority of bridge engineers indicated that their ratings of the overall physical condition of a deteriorated concrete bridge deck are influenced more by the physical condition of traffic-lane areas than by the physical condition of shoulder areas.

2. The five concrete bridge deck rehabilitation decision factors most frequently selected by bridge engineers as being influential are as follows, listed in the order of selection frequency:
• Amount of physical deterioration
• Availability of funds/labor
• Condition of the superstructure
• Volume of traffic (AADT)
• Rate of physical deterioration

3. A majority of bridge engineers indicated that their ratings of the overall physical condition of a concrete bridge are influenced more by the physical condition of the superstructure than by the physical condition of either the deck or the substructure.

4. A majority of bridge engineers indicated that their decisions to repair or rehabilitate concrete bridge substructure components are often significantly affected by whether a decision has been made to repair or rehabilitate the deck. Thus, it may be impractical to quantify terminal damage levels to define the end of functional service life for concrete bridge substructure components.
5.2 CONCLUSIONS

Due to the particular bridge component damage maps upon which the survey engineers based their responses, the conclusions are applicable only to the following concrete bridge components:

- Two-lane bridge decks having a surface area not greater than approximately 9300 square feet.
- Open-type bridge piers having a surface area not greater than approximately 900 square feet.

1. Based on recommended standards, it is likely that the end of functional service life for concrete bridge decks is reached when the percentage of the worst traffic lane surface area that is spalled, delaminated, and patched with asphalt ranges from 9.3% to 13.6%.

2. Based on current standards, it is likely that the end of functional service life for concrete bridge decks is reached when the percentage of the whole deck surface area that is spalled, delaminated, and patched with asphalt ranges from 5.8% to 10.0%.
3. Based on current standards, it is unlikely that the end of functional service life for open-type concrete bridge piers has been reached when the percentage of the surface area of all cap and column surfaces (excluding the horizontal top surface of the cap) that is spalled and has unsound concrete as indicated by cracks is 4.1% or less.

4. It is not likely that the end of functional service life for concrete bridge abutments can be quantified as a level of physical damage.
1. The two concrete bridge deck terminal damage levels that were defined in this study are considered to be general estimates. An additional opinion survey of bridge engineers could be conducted to present these terminal damage levels to the bridge engineering community for further validation and refinement.

2. The Cady-Weyers corrosion-deterioration model for concrete bridges (refer to Figure 1) has two axes: damage and time. For public policy and research purposes, it would be useful to be able to predict the age at which a typical concrete bridge deck will reach the terminal damage levels defined in this investigation.

A study attempting to relate the physical deck damage level to deck age (and perhaps environmental condition parameters) could be conducted using a large random sample of bare concrete decks that have never been overlaid. The decks should vary in age and represent the ranges of environmental conditions encountered in the 25 contiguous states that use
de-icing salts. It is possible that deck damage maps could be obtained from State DOT inspection records. Regression analysis could be used in efforts to develop model equations relating the damage level to age. Considering the variability in the mean age-at-overlay values determined in previous studies by Cady and Weyers and Weyers et al. (refer to section 2.2.3), it might be necessary to attempt several separate damage/age models to predict the terminal age for decks exposed to different environmental condition levels.

3. It may be worthwhile to refine the bridge deck mapping method developed in this study. It is possible that use of a video camera rather than a 35mm print camera for recording deck damage images, and use of a digitizing scanner rather than manual digitizing for collecting computer coordinates from the recorded images, could make the photography-based method a feasible option for State DOTs to use for mapping deck damage during routine bridge inspections.
WORKS CITED


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APPENDIX A

Rectification Program [23] and

Sample Coordinate Data File
PROGRAM RECTIFY
***********************************************************************
* RECTIFICATION OF ERDAS .DIG FILES USING AN AFFINE * 
* TRANSFORMATION AND VARIABLE NUMBER OF CONTROL POINTS * 
* IN A LEAST SQUARES ADJUSTED SOLUTION. * 
* VERSION 1.1, SEPT 1987 * 
* By Professor * 
* STEVEN D. JOHNSON * 
***********************************************************************

CHARACTER*16 FNAME,CNAME,PNAME,ONAME
CHARACTER*4 AAAAA
DOUBLE PRECISION XI(4),YI(4),B(3),Q(3,3),R(3),S(3),CX(3),CY(3)
INTEGER GIS,PROJ,TOT,SUM
DOUBLE PRECISION XD(20),YD(20),XC(20),YC(20),X,Y,G,H
DOUBLE PRECISION XMAX,XMIN,YMAX,YMIN
DOUBLE PRECISION ROMG(3,3),VECI(3),VECD(3)
DOUBLE PRECISION HT,FL,OMG,GX,GY,ALPHA,BETA

200 FORMAT (A16)
201 FORMAT (5I5)
202 FORMAT (A4)
203 FORMAT (4I5,':')
204 FORMAT (2F12.2,':')
205 FORMAT (2F12.2)
206 FORMAT (5I5)

WRITE(*,*)
WRITE(*,*)
WRITE(*,*)
WRITE(*,*)  ** RECTIFICATION OF ERDAS .DIG FILES **
WRITE(*,*)  ** by Dr. Steven D. Johnson **
WRITE(*,*)  ** Version 1.0, July 1987 **
WRITE(*,*)
WRITE(*,*)
WRITE(*,*)
WRITE(*,*)

9 WRITE(*,*)
WRITE(*,*)'Enter complete name of your DIGITIZED DATA file
* <e.g. d:fname.DIG>*
WRITE(*,*)
WRITE(*,*)  ** Include drive letter and file name extension**
READ(*,200) FNAME
WRITE(*,*)
WRITE(*,*)
WRITE(*,*)
WRITE(*,*)'Enter complete name of your CONTROL DATA file
*<e.g. d:fname.DIG>''
WRITE(*,*)'
WRITE(*,*)' ** Include drive letter and file name extension'
READ(*,200) CNAME
WRITE(*,*)'
WRITE(*,*)'
WRITE(*,*)
WRITE(*,*)'Enter file name to be assigned to your RECTIFIED DATA file
*i.e. <e.g. d:fname.DIG>''
WRITE(*,*)'
WRITE(*,*)' ** Include drive letter and file name extension'
READ(*,200) PNAME
WRITE(*,*)'
WRITE(*,*)'
WRITE(*,*)'
WRITE(*,*)'Enter file name to be assigned to your PRINTER OUTPUT file
*i.e. <e.g. d:fname.PRT>''
WRITE(*,*)'
WRITE(*,*)' ** Include drive letter and file name extension'
READ(*,200) ONAME
WRITE(*,*)'
WRITE(*,*)'
WRITE(*,*)'
WRITE(*,*)'***************************************************************************************''

WRITE(*,*)'
WRITE(*,*)'
WRITE(*,*)'INPUT DATA FILE      = ',FNAME
WRITE(*,*)'
WRITE(*,*)'CONTROL DATA FILE = ',CNAME
WRITE(*,*)'
WRITE(*,*)'OUTPUT DATA FILE   = ',PNAME
WRITE(*,*)'
WRITE(*,*)'PRINTER OUTPUT FILE = ',ONAME
WRITE(*,*)'
WRITE(*,*)'
WRITE(*,*)'Accept above filenames (Y or N)'
WRITE(*,*)'
READ(*,202) AAAAA
IF (AAAAA .EQ. 'Y ') THEN
ENDIF

WRITE(*,*)'
WRITE(*,*)'

159
WRITE(*,*)'***************************************************'
WRITE(*,*)'** Opening data file and initializing project files'
WRITE(*,*)'***************************************************'
WRITE(*,*)
WRITE(*,*)
WRITE(*,*)
WRITE(*,*)
OPEN (1,FILE=FNAME,STATUS='OLD',ACCESS='SEQUENTIAL')
OPEN (2,FILE=CNAME,STATUS='OLD',ACCESS='SEQUENTIAL')
OPEN (3,FILE=PNAME,STATUS='UNKNOWN',ACCESS='SEQUENTIAL')
OPEN (4,FILE=ONAME,STATUS='UNKNOWN',ACCESS='SEQUENTIAL')
WRITE(*,*)
WRITE(*,*)
WRITE(*,*)
WRITE(*,*)
WRITE(*,*)
WRITE(*,*)
WRITE(*,*)
WRITE(*,*)
WRITE(*,*)
WRITE(*,*)
WRITE(*,*)
WRITE(*,*)
WRITE(*,*)
WRITE(*,*)
WRITE(*,*)
WRITE(*,*)
WRITE(*,*)
READ(*,205) HT
WRITE(*,*)
WRITE(*,*)
WRITE(*,*)
WRITE(*,*)
WRITE(*,*)
WRITE(*,*)
WRITE(*,*)
READ(*,205) FL
WRITE(*,*)
WRITE(*,*)
WRITE(*,*)
WRITE(*,*)
WRITE(*,*)
WRITE(*,*)
READ(*,205) YCP
READ(1,206) J,GIS,PROJ,NUM,TOT
WRITE(3,201) J,GIS,PROJ,NUM,TOT
SUM = 0
DO 12 I=1,4
  READ(2,205) XC(I),YC(I)
  READ(1,205) XI(I),YI(I)
  DO 13 J=1,3
    Q(I,J) = 0.0
  13
d SUM = SUM + J + 1
12
DO 13 I=1,4
  R(I) = 0.0
  S(I) = 0.0
  DO 13 J=1,3
13
Q(I,J) = 0.0
READ(1,206) J,GIS,PROJ,NUM
READ(2,206) I
DO 15 I=1,4
   READ(1,205) XD(I),YD(I)
   READ(2,205) XC(I),YC(I)

   B(1) = -XD(I)
   B(2) = -YD(I)
   B(3) = -1.0
   G = -XC(I)
   H = -YC(I)

   CALL MAMULT (B,1,3,1,B,1,3,1,Q,3,0,-1)
   CALL MAMULT (B,1,3,1,G,1,1,1,R,3,0,-1)
   CALL MAMULT (B,1,3,1,H,1,1,1,S,3,0,-1)

15 CONTINUE
   CALL MAINV (Q,3,3)
   CALL MAMULT (Q,3,3,R,3,1,1,3,CX,3,-1,0)
   CALL MAMULT (Q,3,3,S,3,1,1,3,CY,3,-1,0)

   WRITE(*,*) 'RESIDUALS X,Y'
   DO 20 I=1,4
      VX = CX(1)*XD(I) + CX(2)*YD(I) + CX(3) - XC(I)
      VY = CY(1)*XD(I) + CY(2)*YD(I) + CY(3) - YC(I)
   WRITE(*,*) VX,VY
20 CONTINUE

   WRITE(*,*) 'Accept above solution (Y or N)'
   READ(*,202) AAAAA
   IF (AAAAA .EQ. 'Y') THEN
      ELSE
      GO TO 999
   ENDIF

C READ FIFTH (CENTER) POINT FOR OMEGA CALC
   READ(1,205) XD(5),YD(5)
   X = CX(1)*XD(5) + CX(2)*YD(5) + CX(3)
   Y = CY(1)*XD(5) + CY(2)*YD(5) + CY(3)
   ALPHA = ATAN(YCP/HT)
   BETA = ATAN(Y/FL)
   OMG = ALPHA - BETA
   CALL ROTATE (-OMG,0.0,0.0,ROMG)
   OMG = OMG * 57.29577951
   WRITE (4,*)

161
WRITE (4,*) ' FILE = ', PNAME
WRITE (4,*) ' OMEGA = ', OMG

DO 25 I=1,4
  X = CX(1)*XI(I) + CX(2)*YI(I) + CX(3)
  Y = CY(1)*XI(I) + CY(2)*YI(I) + CY(3)
C APPLY CAMERA MODEL
  VECI(1) = X
  VECI(2) = Y
  VECI(3) = -FL
  CALL MAMULT (ROMG,3,3,3,VECI,3,1,3,VECD,3,-1,0)
  GX = -HT*(VECD(1)/VECD(3))
  GY = -HT*(VECD(2)/VECD(3))
25 WRITE (3,204) GX,GY
  SUM = SUM + 4 + 1

WRITE(3,203) J,GIS,PROJ,NUM

DO 26 I=1,J
  WRITE (3,204) XC(I),YC(I)
26 XMAX = 0.00
XMIN = 1E10
YMAX = 0.00
YM = 1E10
IFLG = 0
WRITE(4,*)
WRITE(4,*)
WRITE(4,*) 'REFERENCE POINTS FOLLOW'
WRITE(4,*)

27 SUM = SUM + J + 1
PRINT *, ' SUM ', SUM
PRINT *, ' TOT ', TOT

IF (SUM .LT. TOT) THEN
  READ(1,206,END=35) J,GIS,PROJ,NUM
  WRITE(*,*)
  WRITE(*,*) 'BEGIN DATA TYPE', J
  WRITE(*,*) 'GIS VALUE ', GIS
  WRITE(3,203) J,GIS,PROJ,NUM
  DO 30 I=1,J
    READ(1,205,END=35) XD(I),YD(I)
    X = CX(1)*XD(I) + CX(2)*YD(I) + CX(3)
    Y = CY(1)*XD(I) + CY(2)*YD(I) + CY(3)
  30 READ(1,205,END=35) XD(I),YD(I)
  READ(1,206,END=35) J,GIS,PROJ,NUM
  WRITE(*,*)
  WRITE(*,*) 'BEGIN DATA TYPE', J
  WRITE(*,*) 'GIS VALUE ', GIS
  WRITE(3,203) J,GIS,PROJ,NUM
  DO 30 I=1,J
    READ(1,205,END=35) XD(I),YD(I)
    X = CX(1)*XD(I) + CX(2)*YD(I) + CX(3)
    Y = CY(1)*XD(I) + CY(2)*YD(I) + CY(3)
  30 READ(1,205,END=35) XD(I),YD(I)
  READ(1,206,END=35) J,GIS,PROJ,NUM
  WRITE(*,*)
  WRITE(*,*) 'BEGIN DATA TYPE', J
  WRITE(*,*) 'GIS VALUE ', GIS
  WRITE(3,203) J,GIS,PROJ,NUM
  DO 30 I=1,J
    READ(1,205,END=35) XD(I),YD(I)
    X = CX(1)*XD(I) + CX(2)*YD(I) + CX(3)
    Y = CY(1)*XD(I) + CY(2)*YD(I) + CY(3)
  30 READ(1,205,END=35) XD(I),YD(I)

162
C APPLY CAMERA MODEL
    VECI(1) = X
    VECI(2) = Y
    VECI(3) = -FL
    CALL MANMUL (ROMG,3,3,VECI,3,1,3,VECD,3,-1,0)
    GX = -HT*(VECD(1)/VECD(3))
    GY = -HT*(VECD(2)/VECD(3))
    IF (GX .GT. XMAX) XMAX=GX
    IF (GX .LT. XMIN) XMIN=GX
    IF (GY .GT. YMAX) YMAX=GY
    IF (GY .LT. YMIN) YMIN=GY
    IF (IFLG .EQ. 0) WRITE(4,204) GX,GY
    WRITE (3,204) GX,GY
    IFLG = 1
    GO TO 27
ENDIF

30 WRITE (3,204) GX,GY

ENDIF

35 WRITE(*,*) 'END OF DATA FILE REACHED'
    WRITE(*,*)
    WRITE(*,*) 'X MAX = ',XMAX
    WRITE(*,*) 'X MIN = ',XMIN
    WRITE(*,*)
    WRITE(*,*) 'Y MAX = ',YMAX
    WRITE(*,*) 'Y MIN = ',YMIN
    WRITE(4,*)
    WRITE(4,*) 'LIMITS FOLLOW'
    WRITE(4,*)
    WRITE(4,*) 'X MAX = ',XMAX
    WRITE(4,*) 'X MIN = ',XMIN
    WRITE(4,*)
    WRITE(4,*) 'Y MAX = ',YMAX
    WRITE(4,*) 'Y MIN = ',YMIN

STOP

999 WRITE(*,*) 'RECTIFICATION HALTED BY USER'
STOP
END

163
SAMPLE COORDINATE FILE FROM DIGITIZING PHOTOGRAPH

Units in millimeters.
Origin near lower left corner of photograph.

Left column: x coordinates.
Right column: y coordinates.

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</tbody>
</table>
APPENDIX B

Survey Kit

Component damage maps not included.
INSTRUCTIONS
GETTING STARTED

Dear survey participant,

Thank you for helping us! You have been selected as one of only a hundred engineers from the snowbelt states of the U.S. to participate in this survey to define the service life of concrete bridge components. The success of this important survey depends entirely on careful input from each participant, and we greatly appreciate your cooperation.

Please, do not be intimidated by the amount of material enclosed. We expect your participation in this survey to take about 90 minutes. We would like to receive your responses no later than Friday, April 24, 1992.

Please do not collaborate with anyone on this survey. We are interested in your opinions.

SURVEY BACKGROUND AND OBJECTIVE

This survey was developed at Virginia Tech as part of a research project on concrete bridge rehabilitation. The project is sponsored by the Strategic Highway Research Program (SHRP).

Our project is limited to concrete bridges that deteriorate from chloride-induced corrosion of steel reinforcement bars. Specifically, we are studying bridges that receive chlorides through applications of de-icing salts (not through saltwater exposure in a marine environment).

The objective of this survey is to define the end of functional service life for concrete bridge decks, piers, and abutments that deteriorate due to exposure to de-icing salts.

SURVEY OVERVIEW

In this survey, you will be asked to evaluate maps of bridge components. Each component map shows deteriorated areas in different colors. You will be asked to evaluate three decks, two piers, and one abutment.
All of the component maps you will evaluate were painstakingly made from existing bridges from snowbelt states. Many engineers have found these maps to be interesting and unique. You are welcome to keep the maps as a token of our appreciation for your help.

INSTRUCTIONS

1. Make sure you have received the following materials in your Survey Kit:

   -- five paper-clipped Packets, labelled "Packet #1" to "Packet #5"
   -- a "Color Code Legend for Decks" attached to these instructions
   -- a "Scale" attached to these instructions
   -- an envelope addressed to Virginia Tech so you can return the Survey Response Forms

   If any materials are missing, please call Mike Fitch at (703)-231-4217.

2. Carefully review the green sheets attached, "DEFINITIONS FOR THE SURVEY".

3. Work on the five packets in order, starting with "Packet #1" and ending with "Packet #5". Instructions are provided with each Packet.

4. When you have completed "Packet #5", put the Survey Response Forms in the envelope addressed to Virginia Tech and mail it.

5. If you have any questions about this survey, do not hesitate to call Mike Fitch at (703)-231-4217.

Thank you again, and we hope you enjoy the survey!
DEFINITIONS FOR THE SURVEY

Use the following terms as they are defined when working on the survey.

1. "Bridge Components"

This survey involves three bridge components: decks, piers, and abutments.

We are using the term "pier" to describe the sum of a pier cap and all columns that support it.

All bridge components represented in this survey are made of reinforced concrete, and their exposed surfaces are bare concrete (for example, all the decks have concrete riding surfaces). All the components are from existing bridges from the snowbelt states of the U.S.

2. "Rehabilitation"

For decks, we define rehabilitation as REMOVAL OF UNSOUND CONCRETE, PATCHING, AND OVERLAY.

For substructure components, we define rehabilitation as REMOVAL OF UNSOUND CONCRETE, PATCHING, AND PARTIAL OR COMPLETE ENCASEMENT OF THE COMPONENT.

3. "Rehabilitation Condition"

Assume that every concrete bridge component exposed to de-icing salts eventually deteriorates to a physical condition that justifies rehabilitation. We define this physical condition as the Rehabilitation Condition.

The "true" Rehabilitation Condition is reached when the component has reached the end of its initial functional service life, and significant correction is necessary to return it to an acceptable level of service.

The local/national economy may affect whether rehabilitation is "justified". Assume an "average" economy of the past ten years.
4. "LOCAL STANDARDS Rehabilitation Condition"

You are familiar with the physical condition of a bridge component at the time it is rehabilitated in your engineering district. This is the Local Standards Rehabilitation Condition.

5. "SNOWBELT STANDARDS Rehabilitation Condition"

Assume you are a member of a committee consisting of all Bridge Engineers from the snowbelt states of the U.S. This large committee is responsible for reaching a consensus concerning the Rehabilitation Condition for decks, piers, and abutments.

The committee is aware that there are approximately 60,000 bridges in the United States whose decks could be described as "badly deteriorated". Many bridges also have "badly deteriorated" substructure components.

The "average" availability of federal funds for bridge rehabilitation is discussed. It is agreed that not every bridge component showing some deterioration should be rehabilitated immediately. However, it is also agreed that the public expects a reasonable level of service from bridges.

After a heated debate, the committee defines, for each bridge component, a physical condition that justifies rehabilitation. This is the Snowbelt Standards Rehabilitation Condition. You will be asked to estimate what the Snowbelt Standards Rehabilitation Condition would probably be for each component.

We are not asking you to try to guess what other snowbelt states think about rehabilitation; that would be impossible. Instead, we ask that you estimate standards that you think are desirable and reasonable, and could be applied to all snowbelt states.

6. "The Time to Rehabilitate"

The Time to Rehabilitate is the time when a concrete bridge component reaches its Rehabilitation Condition. It may be in the past, present or future. For example:
The Time to Rehabilitate was in the past:
"The component should have been rehabilitated about five years ago"

The Time to Rehabilitate is in the present:
"The component should be rehabilitated now"

The Time to Rehabilitate is in the future:
"The component should be rehabilitated in about five years"

To estimate the Time to Rehabilitate for a bridge component, you must first decide WHAT THE REHABILITATION CONDITION IS for the component, using either Local or Snowbelt Standards as defined above. You must then estimate the RATE AT WHICH THE COMPONENT IS DETERIORATING to determine when it was, or will be, in Rehabilitation Condition.

Many of the items in this Survey Kit ask you to estimate the Time to Rehabilitate for a bridge component. For those items, choose your responses from the pink sheets attached, "ANSWER CHOICES FOR THE TIME TO REHABILITATE".

7. SPECIAL NOTE

Some engineering districts "skew" their Time to Rehabilitate because of their rehabilitation techniques. For example, Vermont districts rehabilitate before decks reach the Rehabilitation Condition, because they believe in waterproofing before delamination begins.

If your engineering district rehabilitates before the "true" Rehabilitation Condition is reached, this should be reflected in your responses using Local Standards.

However, your responses using Snowbelt Standards should be based on the assumption of the deck reaching a "true" Rehabilitation Condition, where rehabilitation is significantly corrective as well as preventive.
ANSWER CHOICES FOR THE TIME TO REHABILITATE

A. It will be more than 20 years before this bridge component should be rehabilitated.

B. This bridge component should be rehabilitated in about 20 years.

C. This bridge component should be rehabilitated in about 18 years.

D. This bridge component should be rehabilitated in about 16 years.

E. This bridge component should be rehabilitated in about 14 years.

F. This bridge component should be rehabilitated in about 12 years.

G. This bridge component should be rehabilitated in about 10 years.

H. This bridge component should be rehabilitated in about 8 years.

I. This bridge component should be rehabilitated in about 6 years.

J. This bridge component should be rehabilitated in about 4 years.

K. This bridge component should be rehabilitated in about 2 years.

L. This bridge component should be rehabilitated now.

M. This bridge component should have been rehabilitated about 2 years ago.

N. This bridge component should have been rehabilitated about 4 years ago.

O. This bridge component should have been rehabilitated about 6 years ago.
P. This bridge component should have been rehabilitated about 8 years ago.

Q. This bridge component should have been rehabilitated about 10 years ago.

R. This bridge component should have been rehabilitated about 12 years ago.

S. This bridge component should have been rehabilitated about 14 years ago.

T. This bridge component should have been rehabilitated about 16 years ago.

U. This bridge component should have been rehabilitated about 18 years ago.

V. This bridge component should have been rehabilitated about 20 years ago.

W. This bridge component should have been rehabilitated more than 20 years ago.
Evaluations of deck damage maps; same format for all three packets.
SURVEY RESPONSE FORM: DECK # ___

PART I. INSTRUCTIONS

Please print your name here: ______________________

Make sure you use the map of Deck # ___ to fill out this Survey Response Form.

Please expect to spend about 15 minutes working on this Packet. It will be helpful to separate the map from this Survey Response Form before you begin.

The purpose of this Packet is to determine your judgements about the physical condition of the bridge deck represented by the deck map.

The map suggests the physical condition of the deck by showing deterioration indicators: spalls, delaminations, cracks, asphalt patches, and concrete patches. Each indicator is represented by a color. Use the "Color Code Legend for Decks" to identify each indicator. Use the "Scale" provided to measure sizes of deteriorated areas.

For your convenience, the map is surrounded by a border that has tick marks every 10 feet.

PART II. INFORMATION PROVIDED

Assume the Following:

1. The physical deterioration (delamination, cracking, and spalling) is initiated primarily by chloride-induced corrosion of the top mat of steel reinforcement bars in the deck.

2. De-icing salts are the source of the chlorides causing the corrosion. Saltwater from a marine environment is not a source of the chlorides.
3. The deck is corroding and deteriorating at a roughly linear rate over time.

Thus, given the present physical condition of the deck and its age, you can estimate the physical condition of the deck at some time in the past or future.

Given for This Deck:

1. The deck was constructed and put into use ____ years ago.

2. The average annual daily traffic (AADT) is ________ vehicles per day.

3. Typical traffic speed is _____________ 45 mph.
PART III. EVALUATION OF DETERIORATION INDICATORS

Please examine the deck map carefully. The map shows one or more deterioration indicators: spalls, delaminations, cracks, asphalt patches, and concrete patches. There are four factors associated with each indicator: number, size, location, and total surface area. These factors are listed in items 1 through 20.

For each item, evaluate the extent to which the factor impacts on your assessment of the PRESENT PHYSICAL CONDITION of this deck. Please respond by circling A, B, C, or D, which are defined below.

A. "This factor has A LOT OF IMPACT on my assessment of the present physical condition this deck."

B. "This factor has SOME IMPACT on my assessment of the present physical condition of this deck."

C. "This factor has LITTLE OR NO IMPACT on my assessment of the present physical condition of this deck."

D. "This factor DOES NOT APPEAR on this deck."

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<thead>
<tr>
<th>FACTOR</th>
<th>YOUR RESPONSE</th>
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</thead>
<tbody>
<tr>
<td>1. The number of spalls:</td>
<td>A B C D</td>
</tr>
<tr>
<td>2. Sizes of individual spalls:</td>
<td>A B C D</td>
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<tr>
<td>3. Locations of spalls:</td>
<td>A B C D</td>
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<td>4. Total surface area spalled:</td>
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<td>5. The number of delaminations:</td>
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<td>6. Sizes of individual delaminations:</td>
<td>A B C D</td>
</tr>
<tr>
<td>7. Locations of delaminations:</td>
<td>A B C D</td>
</tr>
<tr>
<td>8. Total surface area delaminated:</td>
<td>A B C D</td>
</tr>
<tr>
<td>9. The number of cracks:</td>
<td>A B C D</td>
</tr>
<tr>
<td>10. Lengths of individual cracks:</td>
<td>A B C D</td>
</tr>
<tr>
<td>11. Locations of cracks:</td>
<td>A B C D</td>
</tr>
<tr>
<td>12. Total lineal feet of cracking:</td>
<td>A B C D</td>
</tr>
<tr>
<td>13. The number of asphalt patches:</td>
<td>A B C D</td>
</tr>
<tr>
<td>14. Sizes of individual asphalt patches:</td>
<td>A B C D</td>
</tr>
<tr>
<td>15. Locations of asphalt patches:</td>
<td>A B C D</td>
</tr>
</tbody>
</table>
16. Total surface area patched with asphalt: A B C D
17. The number of concrete patches: A B C D
18. Sizes of individual concrete patches: A B C D
19. Locations of concrete patches: A B C D
20. Total surface area patched with concrete: A B C D
PART IV. EVALUATION OF THE PRESENT PHYSICAL CONDITION OF THE DECK RELATIVE TO THE REHABILITATION CONDITION

You will be asked to examine this deck map and decide if the bridge deck should have been rehabilitated at some time in the past; should be rehabilitated now; or should be rehabilitated at some time in the future.

For decks, we define rehabilitation as REMOVAL OF UNSOUND CONCRETE, PATCHING, AND OVERLAY.

Refer to the deck map to assess the PRESENT PHYSICAL CONDITION of this deck. Consider the age of the deck to estimate the RATE at which it is deteriorating.

Consider the PRESENT PHYSICAL CONDITION, RATE, and TRAFFIC INFORMATION to answer items 1 and 2.

1. Evaluation Relative to the Local Standards Rehabilitation Condition

Estimate the Local Standards Rehabilitation Condition for concrete bridge decks. Relative to the Local Standards Rehabilitation Condition of your engineering district, when do you think this deck should have been, or should be, rehabilitated?

Select the letter of your answer from the pink sheets "ANSWER CHOICES FOR THE TIME TO REHABILITATE", and write it below.

The Time to Rehabilitate using Local Standards: ___

2. Evaluation Relative to the Snowbelt Standards Rehabilitation Condition

Estimate the Snowbelt Standards Rehabilitation Condition for concrete bridge decks. Relative to the Snowbelt Standards Rehabilitation Condition, when do you think this deck should have been, or should be, rehabilitated?
Select the letter of your answer from the pink sheets "ANSWER CHOICES FOR THE TIME TO REHABILITATE", and write it below.

The Time to Rehabilitate using Snowbelt Standards: ___

PART V. RECOMMENDATIONS

Assume this deck map represents a deck in your engineering district. You have been asked to decide what action, if any, should be taken at this time to improve the physical condition of the deck.

Assume the Local Standards of your engineering district. Based on the deterioration shown on the deck map, circle the letter of your choice for items 1 through 3 below.

1. Which treatment would you choose for this deck at this time?
   A. Do nothing
   B. Repair: patch damaged areas
   C. Rehabilitation: remove unsound concrete, patch, and overlay

2. Answer this question only if you chose "Repair" in item 1.
   Which type(s) of patching would you choose?
   A. Fill spalls with bituminous concrete
   B. Cut out areas of unsound concrete and fill with some type of hydraulic cement concrete
   C. Both A and B
3. Answer these questions only if you chose "Rehabilitation" in item 1.

What material would you use to patch with before overlay?

A. Portland cement concrete  
B. Other hydraulic cement concrete  
C. Other; please identify: ______________________

Which type of overlay would you specify?

A. Portland cement concrete overlay  
B. Portland cement concrete overlay with a sealer  
C. Micro-silica portland cement concrete overlay  
D. Other hydraulic cement concrete overlay  
   Please identify: ______________________
E. Latex modified concrete overlay  
F. Low slump dense concrete overlay  
G. Bituminous concrete overlay on top of membrane  
H. Bituminous concrete overlay without membrane  
I. Thin polymer overlay  
J. Other; please identify: ______________________

END OF SURVEY RESPONSE FORM FOR THIS PACKET
PACKET #4

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PART I. INSTRUCTIONS

Please print your name here: ______________________

Please expect to spend about 15 minutes working on this Packet. It will be helpful to separate the maps from this Survey Response Form before you begin.

The purpose of this Packet is to determine your judgements about the physical condition of the bridge substructure components represented by the component maps.

You have been provided with component maps for two piers and one abutment. We are using the term "pier" to describe the sum of a pier cap and all columns that support it.

The maps suggest the physical condition of the components by showing the deterioration indicators: spalls, cracks, and patches. Refer to the Legend at the bottom left of each map to identify each indicator by color. Use the "Scale" provided to measure sizes of deteriorated areas.

PART II. INFORMATION PROVIDED

Assume the Following:

1. The physical deterioration (cracking and spalling) is initiated primarily by chloride-induced corrosion of steel reinforcement bars.

2. De-icing salts are the source of the chlorides causing the corrosion. Salt water from a marine environment is not a source of the chlorides.

3. Each substructure component is corroding and deteriorating at a roughly linear rate over time.

Thus, given the present physical condition of the component and its age, you can estimate the physical condition of the component at some time in the past or future.
4. These substructure components are not necessarily from the same bridge; each should be evaluated as an isolated component.

5. The abutment may show vertical cracks not caused by corrosion.

Given for These Components:

1. Pier # ____ was constructed and put into use ____ years ago.

2. Pier # ____ was constructed and put into use ____ years ago.

3. Abutment # ____ was constructed and put into use ____ years ago.
PART III.

Assume, for each component, that the deck supported by the component will not be rehabilitated in the near future.

Estimate the Local Standards Rehabilitation Condition for each substructure component to answer the items below.

Assume you have been asked to decide what action, if any, should be taken to at this time to improve the physical condition of each substructure component shown.

Examine each component map to assess the PRESENT PHYSICAL CONDITION. In the "RECOMMENDATION" column, circle the letter of your recommendation. Choices A, B, and C are explained on the blue sheet attached, "ANSWER CHOICES FOR SUBSTRUCTURE COMPONENTS".

Refer to the ages "Given for These Substructure Components" in Part I to estimate the RATE at which each component is deteriorating. In the "TIME TO REHABILITATE" column, write in the letter from the pink sheets, "ANSWER CHOICES FOR THE TIME TO REHABILITATE", that reflects when you think the component should have been, or should be, rehabilitated.

For substructure components, we define rehabilitation as REMOVAL OF UNSOUND CONCRETE, PATCHING, AND PARTIAL OR COMPLETE ENCASEMENT OF THE COMPONENT.

"DECK ABOVE IS NOT BEING REHABILITATED"

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<th>LOCAL STANDARDS</th>
<th>LOCAL STANDARDS RECOMMENDATION</th>
<th>LOCAL STANDARDS TIME TO REHABILITATE</th>
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<tbody>
<tr>
<td>1. Pier # ____</td>
<td>A</td>
<td>B</td>
<td>C</td>
</tr>
<tr>
<td>2. Pier # ____</td>
<td>A</td>
<td>B</td>
<td>C</td>
</tr>
<tr>
<td>3. Abut. # ____</td>
<td>A</td>
<td>B</td>
<td>C</td>
</tr>
</tbody>
</table>

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PART IV.

Assume, for each component, that the deck supported by the component will not be rehabilitated in the near future.

Estimate the Snowbelt Standards Rehabilitation Condition for each substructure component to answer the items below.

Assume you have been asked to decide what action, if any, should be taken to at this time to improve the physical condition of each substructure component shown.

Examine each component map to assess the present physical condition. In the "RECOMMENDATION" column, circle the letter of your recommendation. Choices A, B, and C are explained on the blue sheet attached, "ANSWER CHOICES FOR SUBSTRUCTURE COMPONENTS".

Refer to the ages "Given for These Substructure Components" in Part I to estimate the rate at which each component is deteriorating. In the "TIME TO REHABILITATE" column, write in the letter from the pink sheets, "ANSWER CHOICES FOR THE TIME TO REHABILITATE", that reflects when you think the component should have been, or should be, rehabilitated.

For substructure components, we define rehabilitation as removal of unsound concrete, patching, and partial or complete encasement of the component.

"DECK ABOVE IS NOT BEING REHABILITATED"

<table>
<thead>
<tr>
<th>SUBSTRUCTURE COMPONENT</th>
<th>SNOWBELT STANDARDS RECOMMENDATION</th>
<th>SNOWBELT STANDARDS TIME TO REHABILITATE</th>
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<tr>
<td>1. Pier #</td>
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<tr>
<td>2. Pier #</td>
<td>A B C</td>
<td></td>
</tr>
<tr>
<td>3. Abut. #</td>
<td>A B C</td>
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</tbody>
</table>

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PART V.

Assume, for each component, that a decision has been made to rehabilitate the deck the component supports.

Does the assumption that the deck is being rehabilitated change any of your previous recommendations for treating the substructure components? Circle the letter of your answer.

A. Yes
B. No

If you answered "Yes", complete the items below.

Assume you have been asked to decide what action, if any, should be taken to at this time to improve the physical condition of each substructure component.

Examine each component map to assess the PRESENT PHYSICAL CONDITION. For both the Local Standards column and the Snowbelt Standards column, circle the letter of your recommendation. Choices A, B, and C are explained on the blue sheet attached, "ANSWER CHOICES FOR SUBSTRUCTURE ITEMS".

Individual responses for this part may or may not be different than your responses for Parts III and IV.

"DECK ABOVE IS BEING REHABILITATED"

<table>
<thead>
<tr>
<th>SUBSTRUCTURE COMPONENT</th>
<th>LOCAL STANDARDS</th>
<th>SNOWBELT STANDARDS</th>
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</thead>
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<td>RECOMMENDATION</td>
<td>RECOMMENDATION</td>
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<td>A B C</td>
</tr>
<tr>
<td>2. Pier # _____</td>
<td>A B C</td>
<td>A B C</td>
</tr>
<tr>
<td>3. Abut. # _____</td>
<td>A B C</td>
<td>A B C</td>
</tr>
</tbody>
</table>

END OF SURVEY RESPONSE FORM FOR THIS PACKET
ANSWER CHOICES FOR SUBSTRUCTURE ITEMS

Use these answer choices for all items that ask you for a RECOMMENDATION of what action, if any, should be taken to improve the physical condition of a substructure component.

A. "Do nothing to this substructure component at this time."

B. "Repair this substructure component."

We define repair as correction of existing spalls, delaminations, and cracks.

C. "Rehabilitate this substructure component."

We define rehabilitation as removal of unsound concrete, patching, and partial or complete encasement of the component.
EVALUATION OF SURVEY

1. Approximately how much time did you spend working on this Survey Kit?


2. Were there any instructions that were unclear or confusing to you? Please identify.


3. Have you made any responses that should be disregarded because you were unsure of the instructions or answer choices? Please identify by writing "DISREGARD" next to these responses on the Survey Response Forms.


4. In general, do you feel comfortable with the answers you provided using Snowbelt Standards? Please circle the number that indicates your response.

   YES 1 2 3 SOMEWHAT 4 NO 5

   Comments:


5. How could this Survey Kit be improved? Please write any suggestions.


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APPENDIX C

Background Deck Data and Opinion Survey Responses Used to
Develop Rehabilitation Prediction Models for
Concrete Bridge Decks
Table C-1 presents background deck data for potential predictor variables that were used to develop deck rehabilitation prediction models. The potential predictor variables are defined as follows:

Basic information shown on deck damage map:

- $x_1 =$ surface area of deck (square feet)
- $x_2 =$ % of whole deck spalled
- $x_3 =$ % of whole deck delaminated
- $x_4 =$ % of whole deck patched with asphalt
- $x_5 =$ % of whole deck patched with concrete
- $x_6 =$ lineal feet of cracks / surface area of deck (feet / square feet)

Information provided to respondents:

- $x_7 =$ age of deck (years)
- $x_8 =$ AADT (vehicles/day)
- $x_9 =$ typical speed of traffic on deck
  \( (> 45 \text{ mph} \text{ or } < 45 \text{ mph}) \)

Total damage for different areas:

- $x_{10} =$ % of whole deck spalled, delaminated, patched with asphalt, and patched with concrete
- $x_{11} =$ % of worst traffic lane spalled, delaminated, patched with asphalt, and patched with concrete
- $x_{12} =$ % of both traffic lanes spalled, delaminated, patched with asphalt, and patched with concrete
Aggregates of damage:

\[ x_{13} = \% \text{ of whole deck spalled and patched with asphalt} \]

\[ x_{14} = \% \text{ of whole deck spalled, delaminated, and patched with asphalt} \]

\[ x_{15} = \% \text{ of worst traffic lane delaminated} \]

\[ x_{16} = \% \text{ of worst traffic lane spalled and patched with asphalt} \]

\[ x_{17} = \% \text{ of worst traffic lane spalled, delaminated, and patched with asphalt} \]

\[ x_{18} = \% \text{ of both traffic lanes delaminated} \]

\[ x_{19} = \% \text{ of both traffic lanes spalled and patched with asphalt} \]

\[ x_{20} = \% \text{ of both traffic lanes spalled, delaminated, and patched with asphalt} \]

The engineers' "Time to Rehabilitate" responses for the 18 deck maps are presented in Table C-2. The responses are presented as Set A and Set B, the half-size cross-validation data sets created by randomly selecting responses from the full data set.
Table C-1. Data for potential predictor variables used to develop deck rehabilitation prediction models.

<table>
<thead>
<tr>
<th>Deck Name</th>
<th>Potential Predictor Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>x₁</td>
<td>x₂</td>
</tr>
<tr>
<td>VA-1</td>
<td>5194</td>
</tr>
<tr>
<td>VA-2</td>
<td>6027</td>
</tr>
<tr>
<td>VA-3</td>
<td>4791</td>
</tr>
<tr>
<td>PA-1</td>
<td>3921</td>
</tr>
<tr>
<td>PA-2</td>
<td>7028</td>
</tr>
<tr>
<td>MI-1</td>
<td>7476</td>
</tr>
<tr>
<td>MI-2</td>
<td>9348</td>
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<td>MI-3</td>
<td>4641</td>
</tr>
<tr>
<td>WI-1</td>
<td>5152</td>
</tr>
<tr>
<td>WI-2</td>
<td>6720</td>
</tr>
<tr>
<td>WI-3</td>
<td>5991</td>
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<td>4601</td>
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<td>OH-1</td>
<td>7068</td>
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</tr>
<tr>
<td>OH-4</td>
<td>6612</td>
</tr>
<tr>
<td>OH-5</td>
<td>5176</td>
</tr>
<tr>
<td>OH-6</td>
<td>5472</td>
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¹Note: The deck for VA-2 was found to have been overlaid with concrete in the past. The age provided to the respondents, eight years, is the time since overlay.
Table C-1. Data for potential predictor variables used to develop deck rehabilitation prediction models (continued).

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<td>5600</td>
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<td>PA-2</td>
<td>2500</td>
</tr>
<tr>
<td>MI-1</td>
<td>4500</td>
</tr>
<tr>
<td>MI-2</td>
<td>3300</td>
</tr>
<tr>
<td>MI-3</td>
<td>5400</td>
</tr>
<tr>
<td>WI-1</td>
<td>100</td>
</tr>
<tr>
<td>WI-2</td>
<td>4000</td>
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<tr>
<td>WI-3</td>
<td>300</td>
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<tr>
<td>WI-4</td>
<td>2600</td>
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<tr>
<td>OH-1</td>
<td>15400</td>
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<td>OH-2</td>
<td>15400</td>
</tr>
<tr>
<td>OH-3</td>
<td>11500</td>
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<tr>
<td>OH-5</td>
<td>13600</td>
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<td>OH-6</td>
<td>15500</td>
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Table C-1. Data for potential predictor variables used to develop deck rehabilitation prediction models (continued).

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<td>1.4</td>
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<tr>
<td>VA-3</td>
<td>9.6</td>
</tr>
<tr>
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<td>16.2</td>
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<td>4.7</td>
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<tr>
<td>OH-4</td>
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<tr>
<td>OH-5</td>
<td>7.8</td>
</tr>
<tr>
<td>OH-6</td>
<td>8.8</td>
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</table>
Table C-2A. Engineers' "Time to Rehabilitate" responses for decks; Set A.

<table>
<thead>
<tr>
<th>Deck Name</th>
<th>&quot;Time to Rehabilitate&quot; Responses</th>
</tr>
</thead>
<tbody>
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<td></td>
<td>Snowbelt Standards</td>
</tr>
<tr>
<td>VA-1</td>
<td>-2, 4, 8, 18</td>
</tr>
<tr>
<td>VA-2</td>
<td>-8, -6, -6</td>
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<tr>
<td>VA-3</td>
<td>-14, -4, 0, 2</td>
</tr>
<tr>
<td>PA-1</td>
<td>4, 8, 10, 10</td>
</tr>
<tr>
<td>PA-2</td>
<td>-6, 0, 0, 0, 2</td>
</tr>
<tr>
<td>MI-1</td>
<td>-14, -10, -2, -2</td>
</tr>
<tr>
<td>MI-2</td>
<td>-10, -6, -6, -4, -4</td>
</tr>
<tr>
<td>MI-3</td>
<td>-2, 0, 2, 4</td>
</tr>
<tr>
<td>WI-1</td>
<td>-30, -14, -16, -10, -8</td>
</tr>
<tr>
<td>WI-2</td>
<td>-8, -4, 8</td>
</tr>
<tr>
<td>WI-3</td>
<td>-6, -4, 0</td>
</tr>
<tr>
<td>WI-4</td>
<td>-4, -4, -4, -2, 2, 6</td>
</tr>
<tr>
<td>OH-1</td>
<td>-4, -2, 0, 0, 0</td>
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<tr>
<td>OH-2</td>
<td>-8, -2, -2, 0, 2</td>
</tr>
<tr>
<td>OH-3</td>
<td>0, 10, 10, 12</td>
</tr>
<tr>
<td>OH-4</td>
<td>-4, -2, 2, 6, 10</td>
</tr>
<tr>
<td>OH-5</td>
<td>-4, -4, -2, -2, 0</td>
</tr>
<tr>
<td>OH-6</td>
<td>0, 0, 4, 4</td>
</tr>
</tbody>
</table>
Table C-2B. Engineers' "Time to Rehabilitate" responses for decks; Set B.

<table>
<thead>
<tr>
<th>Deck Name</th>
<th>&quot;Time to Rehabilitate&quot; Responses</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Snowbelt Standards</td>
</tr>
<tr>
<td>VA-1</td>
<td>-4, -2, 0, 0</td>
</tr>
<tr>
<td>VA-2</td>
<td>-16, -4, -4</td>
</tr>
<tr>
<td>VA-3</td>
<td>-20, -10, 0, 0</td>
</tr>
<tr>
<td>PA-1</td>
<td>0, 0, 6, 12</td>
</tr>
<tr>
<td>PA-2</td>
<td>0, 0, 6, 10, 18</td>
</tr>
<tr>
<td>MI-1</td>
<td>-4, 0, 2, 6</td>
</tr>
<tr>
<td>MI-2</td>
<td>-14, -14, -8, -6</td>
</tr>
<tr>
<td>MI-3</td>
<td>-6, -4, 0, 0</td>
</tr>
<tr>
<td>WI-1</td>
<td>-4, -4, -4, -4, -2</td>
</tr>
<tr>
<td>WI-2</td>
<td>0, 6, 8, 12</td>
</tr>
<tr>
<td>WI-3</td>
<td>-30, -10, -6</td>
</tr>
<tr>
<td>WI-4</td>
<td>-8, 0, 2, 4, 10</td>
</tr>
<tr>
<td>OH-1</td>
<td>-10, -6, 0, 0, 0</td>
</tr>
<tr>
<td>OH-2</td>
<td>-6, -4, -2, 0, 0</td>
</tr>
<tr>
<td>OH-3</td>
<td>-4, 0, 0, 0, 8</td>
</tr>
<tr>
<td>OH-4</td>
<td>-2, 0, 8, 16</td>
</tr>
<tr>
<td>OH-5</td>
<td>-6, -2, 0, 0, 6</td>
</tr>
<tr>
<td>OH-6</td>
<td>-4, -2, -2, 2, 4</td>
</tr>
</tbody>
</table>
APPENDIX D

Background Pier Data and Opinion Survey Responses Used to Develop Rehabilitation Prediction Models for Concrete Bridge Piers
Table D-1 presents background pier data for potential predictor variables that were used to develop pier rehabilitation prediction models. The potential predictor variables are defined as follows:

Basic information shown on pier damage map:

\[ x_1 = \text{Surface area of pier (square feet)} \]
\[ x_2 = \% \text{ of pier area spalled} \]
\[ x_3 = \text{lineal feet of cracks per square foot of pier area} \]
\[ x_4 = \% \text{ of pier area patched} \]

Information provided to respondents:

\[ x_5 = \text{age of pier} \]

Aggregates of damage:

\[ x_6 = \% \text{ of pier area spalled and having unsound concrete as indicated by cracks} \]
\[ x_7 = \% \text{ of pier area spalled, patched, and having unsound concrete as indicated by cracks} \]

Engineers' "Time to Rehabilitate" responses for piers are presented in Table D-2. Responses to "Treatment Recommendation" items are presented in Table D-3 (assumption: the deck will not be rehabilitated), and Table D-4 (assumption: the deck will be rehabilitated). The responses in these tables are presented as Set A and Set B, the half-size cross-validation data sets created by randomly selecting responses from the full data set.
Table D-1. Data for potential predictor variables used to develop pier rehabilitation prediction models.

<table>
<thead>
<tr>
<th>Pier Name</th>
<th>Potential Predictor Variables</th>
</tr>
</thead>
<tbody>
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<td></td>
<td>$x_1$</td>
</tr>
<tr>
<td>VA-1 North</td>
<td>808</td>
</tr>
<tr>
<td>VA-2 North</td>
<td>781</td>
</tr>
<tr>
<td>VA-2 South</td>
<td>780</td>
</tr>
<tr>
<td>VA-3 North</td>
<td>752</td>
</tr>
<tr>
<td>VA-3 South</td>
<td>708</td>
</tr>
<tr>
<td>PA-1 South</td>
<td>704</td>
</tr>
<tr>
<td>MI-1 East</td>
<td>900</td>
</tr>
<tr>
<td>MI-3 North</td>
<td>927</td>
</tr>
</tbody>
</table>
Table D-2A. Engineers' "Time to Rehabilitate" responses for piers; Set A.

<table>
<thead>
<tr>
<th>Pier Name</th>
<th>&quot;Time to Rehabilitate&quot; Responses</th>
<th>Snowbelt Standards</th>
<th>Local Standards</th>
</tr>
</thead>
<tbody>
<tr>
<td>VA-1 N</td>
<td>-14, -10, -8, -8, -2</td>
<td>-14, -12, -8, -8, -2</td>
<td></td>
</tr>
<tr>
<td>VA-1 S</td>
<td>-30, -30, -30, -30, -4, 0</td>
<td>-30, -30, -30, -30, -4, 0</td>
<td></td>
</tr>
<tr>
<td>VA-2 N</td>
<td>-30, -12, -8, -4, -2</td>
<td>-30, -12, -8, -6, -4, -2</td>
<td></td>
</tr>
<tr>
<td>VA-2 S</td>
<td>-30, -30, -14, -14, -10</td>
<td>-30, -30, -20, -14, -10</td>
<td></td>
</tr>
<tr>
<td>VA-3 N</td>
<td>-6, -6, 0, 0, 0, 0</td>
<td>-6, -6, -4, 0, 0, 0</td>
<td></td>
</tr>
<tr>
<td>VA-3 S</td>
<td>-20, -18, -10, -8, -2</td>
<td>-30, -18, -8, -6, -2</td>
<td></td>
</tr>
<tr>
<td>PA-1 N</td>
<td>-20, -10, -10</td>
<td>-30, -10, -8</td>
<td></td>
</tr>
<tr>
<td>PA-1 S</td>
<td>-16, -10, -10, -8, -6</td>
<td>-14, -14, -10, -10, -6</td>
<td></td>
</tr>
<tr>
<td>MI-1 W</td>
<td>-20, -14, -10, -6</td>
<td>-20, -14, -6, -6</td>
<td></td>
</tr>
<tr>
<td>MI-1 E</td>
<td>-30, -30, -8, -8, 4</td>
<td>-30, -30, -8, -8, -2</td>
<td></td>
</tr>
<tr>
<td>MI-3 N</td>
<td>-30, -30, -14, -10, -8, 4</td>
<td>-30, -30, -20, -10, -8, -4</td>
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201
Table D-2B. Engineers' "Time to Rehabilitate" responses for piers; Set B.

<table>
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<tr>
<th>Pier Name</th>
<th>&quot;Time to Rehabilitate&quot; Responses</th>
<th>Snowbelt Standards</th>
<th>Local Standards</th>
</tr>
</thead>
<tbody>
<tr>
<td>VA-1 N</td>
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</tr>
<tr>
<td>VA-1 S</td>
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<td>-20, -16, -14, -10</td>
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<tr>
<td></td>
<td>-8, 0, 0</td>
<td>-10, -8, -6</td>
<td></td>
</tr>
<tr>
<td>VA-2 N</td>
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<td>-30, -20, -16, -6, -4, -2, 0</td>
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<td>-30, -8, -6, -6, 0</td>
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<td>-30, -10, -8, -6</td>
<td></td>
</tr>
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<td>PA-1 S</td>
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<td>-30, -30, -30, -10</td>
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<td>MI-1 W</td>
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<td>-30, -30, -30, 6</td>
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<tr>
<td>MI-1 E</td>
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<td>-30, -10, -8, -8, 0</td>
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<tr>
<td>MI-3 N</td>
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<td>-30, -16, -10, -4, -2</td>
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Table D-3A. Engineers' "Treatment Recommendation" responses for piers, assuming the deck will not be rehabilitated; Set A.

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<tr>
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<th>&quot;Treatment Recommendation&quot; Responses</th>
<th>Snowbelt Standards</th>
<th>Local Standards</th>
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<td>VA-2 S</td>
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<td>0, 0, 0, 0, 0, 0</td>
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<td>VA-3 N</td>
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<td>VA-3 S</td>
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<td>0, 0, 0, 0, 0, 1</td>
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<tr>
<td>PA-1 N</td>
<td>0, 1, 1</td>
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<tr>
<td>PA-1 S</td>
<td>0, 0, 0, 0, 0, 0</td>
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Table D-3B. Engineers' "Treatment Recommendation" responses for piers, assuming the deck will not be rehabilitated; Set B.

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<th>&quot;Treatment Recommendation&quot; Responses</th>
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<td>Snowbelt Standards</td>
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<td>VA-1 S</td>
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<tr>
<td>VA-2 N</td>
<td>0, 0, 0, 1, 1, 1</td>
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<td>VA-2 S</td>
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<tr>
<td>VA-3 N</td>
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<td>0, 0, 0, 0, 1</td>
</tr>
<tr>
<td>PA-1 N</td>
<td>0, 1, 1</td>
</tr>
<tr>
<td>PA-1 S</td>
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</tr>
<tr>
<td>MI-1 W</td>
<td>0, 0, 0</td>
</tr>
<tr>
<td>MI-1 E</td>
<td>0, 0, 1, 1, 2</td>
</tr>
<tr>
<td>MI-3 N</td>
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Table D-4A. Engineers' "Treatment Recommendation" responses for piers, assuming the deck will be rehabilitated; Set A.

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<th>&quot;Treatment Recommendation&quot; Responses</th>
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</thead>
<tbody>
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<td>Snowbelt Standards</td>
</tr>
<tr>
<td>VA-1 N</td>
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</tr>
<tr>
<td>VA-1 S</td>
<td>0, 0, 1, 1, 1, 2</td>
</tr>
<tr>
<td>VA-2 N</td>
<td>0, 0, 1, 1, 1, 1</td>
</tr>
<tr>
<td>VA-2 S</td>
<td>0, 0, 1, 1, 1</td>
</tr>
<tr>
<td>VA-3 N</td>
<td>0, 1, 1, 2, 2</td>
</tr>
<tr>
<td>VA-3 S</td>
<td>0, 0, 0, 1, 1</td>
</tr>
<tr>
<td>PA-1 N</td>
<td>1, 1, 1</td>
</tr>
<tr>
<td>PA-1 S</td>
<td>0, 1, 1, 1, 2</td>
</tr>
<tr>
<td>MI-1 W</td>
<td>0, 0, 1, 2</td>
</tr>
<tr>
<td>MI-1 E</td>
<td>0, 1, 1, 1, 2</td>
</tr>
<tr>
<td>MI-3 N</td>
<td>0, 0, 0, 1, 1</td>
</tr>
</tbody>
</table>
Table D-4B. Engineers' "Treatment Recommendation" responses for piers, assuming the deck will be rehabilitated; Set B.

<table>
<thead>
<tr>
<th>Pier Name</th>
<th>&quot;Treatment Recommendation&quot; Responses</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Snowbelt Standards</td>
</tr>
<tr>
<td>VA-1 N</td>
<td>1, 1, 1, 1, 1</td>
</tr>
<tr>
<td>VA-1 S</td>
<td>0, 0, 0, 1, 1, 1, 1</td>
</tr>
<tr>
<td>VA-2 N</td>
<td>1, 1, 1, 1, 1, 2, 2</td>
</tr>
<tr>
<td>VA-2 S</td>
<td>0, 1, 1, 1, 1, 1</td>
</tr>
<tr>
<td>VA-3 N</td>
<td>0, 1, 1, 1, 1</td>
</tr>
<tr>
<td>VA-3 S</td>
<td>0, 0, 0, 1, 1, 1</td>
</tr>
<tr>
<td>PA-1 N</td>
<td>0, 1, 2, 2</td>
</tr>
<tr>
<td>PA-1 S</td>
<td>1, 1, 1, 1, 1</td>
</tr>
<tr>
<td>MI-1 W</td>
<td>0, 0, 2</td>
</tr>
<tr>
<td>MI-1 E</td>
<td>0, 1, 1, 1, 2</td>
</tr>
<tr>
<td>MI-3 N</td>
<td>0, 1, 1, 1, 2</td>
</tr>
</tbody>
</table>
APPENDIX E

Background Abutment Data and Opinion Survey Responses Used in Efforts to Develop Rehabilitation Prediction Models for Concrete Bridge Abutments
Table E-1 presents background abutment data for potential predictor variables that were used in efforts to develop abutment rehabilitation prediction models. The potential predictor variables are defined as follows:

\[ x_1 = \text{surface area of abutment (square feet)} \]
\[ x_2 = \text{lineal feet of all cracks per square foot of abutment area} \]
\[ x_3 = \text{lineal feet of non-vertical cracks per square foot of abutment area} \]
\[ x_4 = \text{age of abutment} \]

Engineers' "Time to Rehabilitate" responses for abutments are presented in Table E-2. Responses to "Treatment Recommendation" items are presented in Table E-3 (assumption: the deck will not be rehabilitated), and Table E-4 (assumption: the deck will be rehabilitated). Unlike the deck and pier responses, the abutment responses were not divided into Set A and Set B for cross-validation purposes, because no workable abutment models were developed using the full data set.
Table E-1. Data for potential predictor variables used in efforts to develop abutment rehabilitation prediction models.

<table>
<thead>
<tr>
<th>Abutment Name</th>
<th>Potential Predictor Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$x_1$</td>
</tr>
<tr>
<td>VA-4 N</td>
<td>234</td>
</tr>
<tr>
<td>OH-2 S</td>
<td>336</td>
</tr>
<tr>
<td>OH-4 W</td>
<td>307</td>
</tr>
<tr>
<td>OH-4 E</td>
<td>361</td>
</tr>
<tr>
<td>OH-5 W</td>
<td>353</td>
</tr>
<tr>
<td>OH-5 E</td>
<td>305</td>
</tr>
</tbody>
</table>
Table E-2. Engineers' "Time to Rehabilitate" responses for abutments.

<table>
<thead>
<tr>
<th>Abut. Name</th>
<th>&quot;Time to Rehabilitate&quot; Responses</th>
<th>Snowbelt Standards</th>
<th>Local Standards</th>
</tr>
</thead>
<tbody>
<tr>
<td>VA-4 N</td>
<td>-30, -20, -14, -10, -8, -6, 0</td>
<td>-30, -14, -14, -12, -10, -10, -10</td>
<td></td>
</tr>
<tr>
<td>OH-2 S</td>
<td>-30, -30, -20, -10, -10, -10, -6, -6, 0</td>
<td>-30, -30, -20, -10, -10, -6, -4</td>
<td></td>
</tr>
<tr>
<td>OH-4 W</td>
<td>-20, -20, -16, -12, -12, -10, -10, -10, -4</td>
<td>-20, -20, -16, -12, -12, -10, -10, -10, -10, -10, -4</td>
<td></td>
</tr>
<tr>
<td>OH-4 E</td>
<td>-30, -30, -30, -14, -10, -8, -8, -8, -2, 0</td>
<td>-30, -30, -30, -14, -14, -10, -8, -8, -2, -2</td>
<td></td>
</tr>
<tr>
<td>OH-5 W</td>
<td>-30, -20, -14, -14, -10, -6, -4, -4</td>
<td>-30, -20, -14, -10, -6, -6, -4, -2, 14</td>
<td></td>
</tr>
<tr>
<td>OH-5 E</td>
<td>-30, -30, -30, -30, -30, -14, -10, -10, -6, 0</td>
<td>-30, -30, -30, -30, -30, -12, -10, -6, -2</td>
<td></td>
</tr>
</tbody>
</table>
Table E-3. Engineers' "Treatment Recommendation" responses for abutments, assuming the deck will not be rehabilitated.

<table>
<thead>
<tr>
<th>Abut. Name</th>
<th>&quot;Treatment Recommendation&quot; Responses</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Snowbelt Standards</td>
</tr>
<tr>
<td>VA-4 N</td>
<td>0, 0, 0, 0, 0, 0, 0, 1, 1</td>
</tr>
<tr>
<td>OH-2 S</td>
<td>0, 0, 0, 1, 1, 1, 1, 1</td>
</tr>
<tr>
<td>OH-4 W</td>
<td>0, 0, 0, 0, 0, 0, 0, 0, 0, 1</td>
</tr>
<tr>
<td>OH-4 E</td>
<td>0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 2</td>
</tr>
<tr>
<td>OH-5 W</td>
<td>0, 0, 0, 0, 0, 0, 0, 1, 1</td>
</tr>
<tr>
<td>OH-5 E</td>
<td>0, 0, 0, 0, 0, 0, 0, 0, 1, 1</td>
</tr>
</tbody>
</table>
Table E-4. Engineers' "Treatment Recommendation" responses for abutments, assuming the deck will be rehabilitated.

<table>
<thead>
<tr>
<th>Abut. Name</th>
<th>&quot;Treatment Recommendation&quot; Responses</th>
<th>Snowbelt Standards</th>
<th>Local Standards</th>
</tr>
</thead>
<tbody>
<tr>
<td>VA-4 N</td>
<td>0, 0, 0, 0, 0, 1, 1, 1</td>
<td>0, 0, 0, 0, 0, 0, 0, 1</td>
<td></td>
</tr>
<tr>
<td>OH-2 S</td>
<td>0, 1, 1, 1, 1, 1, 1, 1</td>
<td>0, 0, 0, 1, 1, 1, 1</td>
<td></td>
</tr>
<tr>
<td>OH-4 W</td>
<td>0, 0, 0, 0, 1, 1, 1, 1, 1, 1</td>
<td>0, 0, 0, 0, 1, 1, 1, 1</td>
<td></td>
</tr>
<tr>
<td>OH-4 E</td>
<td>0, 0, 0, 0, 1, 1, 1, 1, 2, 2</td>
<td>0, 0, 0, 0, 1, 1, 1, 2, 2</td>
<td></td>
</tr>
<tr>
<td>OH-5 W</td>
<td>0, 0, 0, 0, 1, 1, 1, 2, 2</td>
<td>0, 0, 0, 0, 1, 1, 1, 2, 2</td>
<td></td>
</tr>
<tr>
<td>OH-5 E</td>
<td>0, 0, 1, 1, 1, 1, 1, 1</td>
<td>0, 0, 0, 0, 1, 1, 1, 2, 2</td>
<td></td>
</tr>
</tbody>
</table>
VITA

The author, who was born in Baltimore, Maryland on March 20, 1968, started his undergraduate engineering studies at Virginia Tech in September of 1986. While an undergraduate student, he served for one year (1989/90) as Projects Vice President for the student chapter of the American Society of Civil Engineers, and was co-chairman of the chapter's Concrete Canoe Team for two years (1988/89 and 1989/90). He graduated from Virginia Tech with a Bachelor of Science degree in Civil Engineering (May of 1990), and then returned to Virginia Tech to start his Master's degree studies (August of 1990). While a graduate student, he worked as a part-time Research Assistant to administer the Strategic Highway Research Program study that is documented in this thesis. Upon completion of his graduate courses, the author moved to Columbus, Ohio to work as a Research Engineer for CTL Engineering, Inc.

Michael G. Fitch

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