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Preface

This publication contains papers presented at the 12th AASHTO–TRB Maintenance Management Conference held in Annapolis, Maryland, July 19–23, 2009. The objective of this series of conferences is to provide a forum every 3 to 4 years for the exchange of new ideas and developments in the maintenance and operations management of transportation facilities. The conference was hosted by the Maryland State Highway Administration, and jointly sponsored by TRB, AASHTO, and FHWA of the U.S. Department of Transportation. It was integrated into the annual AASHTO Highway Subcommittee on Maintenance meeting and includes papers on asset management, bridge monitoring and planning, environment, maintenance issues in design and construction, management systems, outsourcing and safety, pavement performance and preservation programs, performance-based contracting, quality assurance, roadside, winter services, and workforce development.

The views expressed in the papers contained in this publication are those of the authors and do not necessarily reflect the views of TRB, the National Research Council, or the sponsors of the conference. The papers have not been subjected to the formal TRB peer review process.

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MAINTENANCE QUALITY ASSURANCE

Use of Monte Carlo Simulation to Evaluate the Kansas Department of Transportation's Maintenance Quality Assurance Program

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C. BRYAN YOUNG
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The Kansas Department of Transportation (KDOT) has had a Maintenance Quality Assurance (MQA) program in place since 1999 to evaluate the effectiveness of maintenance activities. KDOT samples 3,360 0.1-mi inspection sites every October, and rates the effectiveness of specific elements in the following categories: pavement surface, shoulders, roadside, drainage, and traffic guidance. In order to spread this workload out to each of KDOT's 112 subarea maintenance offices, the inspection site selection scheme selects 30 inspection sites in each subarea. Because of the manpower-intensive nature of this effort, there was a natural desire by KDOT to examine ways to improve their results without increasing the number of sampled inspection sites. Three research questions were addressed in this research. First, is the MQA selection model truly random, or is there an inherent bias in the system due to selecting an even number of inspection sites for each subarea? Second, how would the MQA process be affected if there were a buffer included between selected inspection sites? Third, what would be the trade offs to changing the number of inspection sites per subarea? By populating a database of all possible inspection sites in the state network with actual MQA data, filling in the unsampled inspection sites with estimated data, and using Monte Carlo simulation methods, it was possible to run tens of thousands of selection trials and to analyze the distribution of results to understand the range of the possible maintenance ratings that might be expected under various conditions. It was found that there was no apparent bias in the existing selection scheme, a buffer of even 0.5 mi resulted in selection limitations in some of the smallest subareas, and there appeared to be little precision gained by increasing the number of sampled locations. There could be a benefit to reducing the number of inspection sites selected each year, as the distribution of observed overall maintenance ratings changed little when the number of selected inspection sites was reduced from 30 to 15 per subarea.

Maintenance quality assurance (MQA) is an important activity for departments of transportation (DOTs). Properly conducted MQA activities are meant to provide "the planned and systematic actions needed to provide adequate confidence that highway facilities meet specified requirements" (*1*). By sampling segments of the state highway system (or the entire system), a DOT can estimate the effectiveness of its maintenance activities. Additionally, maintenance managers can use the results as a planning tool to identify areas where maintenance efforts were ineffective compared to expectations, providing information on how to prioritize maintenance needs for the next maintenance season.

BACKGROUND OF THE KANSAS MQA PROGRAM

The Kansas DOT (KDOT) has had a MQA program in place since 1999 to evaluate the effectiveness of maintenance activities. Like many states with MQA programs, KDOT samples a portion of their facility in the fall of each year. Specifically, KDOT samples 30 0.1-mi inspection sites in each of the state's 112 maintenance subareas in October of each year. KDOT subareas were originally established so that each would have approximately equal roadway miles, allowing similar workloads for such activities as snow removal and sign maintenance.

The data collection process amounts annually to 3,360 inspection sites or about 3% of the 10,000-mi state roadway network. By spreading the inspection sites evenly across the subareas the MQA workload was also evenly distributed. Additionally, it was believed that this would allow for an even distribution of inspection sites both geographically and by roadway type. These inspections focus on the condition of a variety of roadway categories, including:

- Pavement surface,
- Shoulders,
- Roadside,
- Drainage, and
- Traffic guidance.

Raw data are collected on 31 individual elements, and reported as either a pass (rated a 1) or a fail (rated a 0). Note that not all 31 elements are collected at each inspection site, as some are mutually exclusive. For example, if the roadway is a flexible pavement there are four elements to evaluate (presence of potholes, presence of cracking, presence of rutting, and presence of deformation), but if the pavement is rigid there are four slightly different elements to evaluate (presence of potholes, presence of cracking, presence of faulting, and deterioration of joint sealant). The complete list of elements that could be evaluated at an inspection site is shown in Table 1.

The threshold for passing or failing an individual element depends on the element. For example, pavement surface cracking on a flexible pavement would be considered failing only if more than 120 ft of cracks larger than ¼ in. were observed at the inspection site (*2*). For each category there are several different elements that must be evaluated, and the input of each is weighted based on a formula developed by KDOT to reflect the general importance of each element.

- Pavement surface comprises 29% of the total weight of the maintenance rating;
- Shoulders comprise 19%;
- Roadside comprises 11%;
- Drainage comprises 14%; and
- Traffic guidance comprises 27%.

These ratings were established based on customer surveys and internal reviews regarding the relative importance of each of the categories.

The results of these inspections are published annually as the "Statewide Maintenance Quality Assurance Inspection Results". In this report, the data from all of the inspection sites are aggregated and converted into a 0 to 100 scale for each of the categories listed above. As a

TABLE 1 Statewide MQA Rating Elements

Categories	Subcategories	Elements
Travelway	Flexible pavements	Presence of potholes Presence of cracking Presence of rutting Presence of deformation
	Rigid pavements	Presence of potholes Presence of cracking Presence of faulting Presence of deteriorated joint sealant
Shoulder	Paved	Presence of joint separation Presence of cracking Presence of edge drop-off Presence of deformation
	Unpaved	Presence of edge ruts Drainage conditions Vegetation conditions
Roadside		Vegetation–weeds condition Presence of litter Fencing condition Brush–tree condition Slope erosion condition Side road entrance conditions
Drainage		Condition of curb and gutter Condition of ditch Condition of erosion control devices Condition of culvert pipes Condition of edge and under drains Condition of drainage inlets
Traffic guidance		Condition of warning–regulatory signs Condition of other signs Condition of guard attenuators–barriers Condition of pavement markings

diagnostic tool, the overall results can be used to indicate a general level of the quality of the inspected elements, and can be used to identify trends in these measures, as shown in Figure 1. For example, if pavement quality is shown to have a downward trend over several years, KDOT maintenance staff can use this information to focus additional resources to improve that particular aspect of the roadway.

CONSIDERATIONS FOR CHANGES TO THE KDOT MQA PROCESS

Though the MQA program has produced useful results since 1999, there is a desire within KDOT to determine if additional information or applications can be achieved through changes in data collection methods. As a part of the formal MQA process, KDOT has an established MQA committee consisting of maintenance supervisors and engineers from across the state. This group

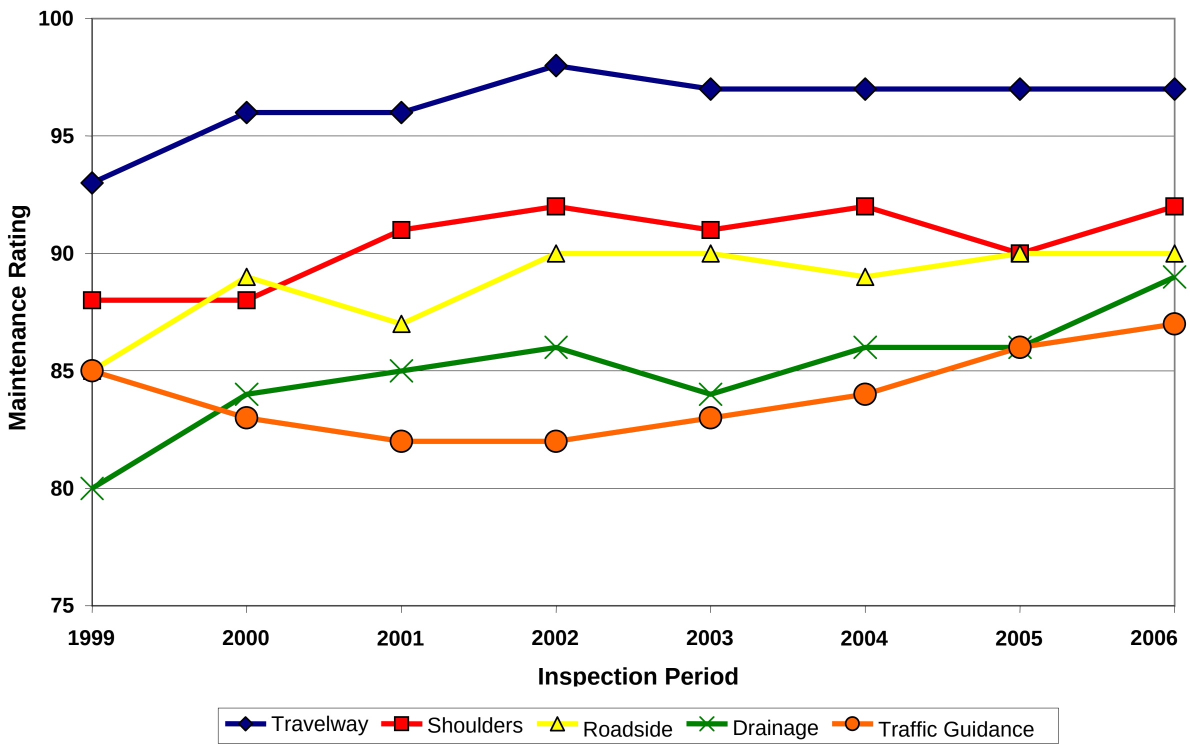

FIGURE 1 Typical statewide KDOT MQA report with maintenance categories shown [adapted from (*3*)].

meets annually to plan training procedures maintenance forces that conduct MQA evaluations, and also discuss possible changes to the overall methodology. Through this committee, KDOT management, and University of Kansas researchers specific questions have arisen about possible changes to the current methodology. This research was conducted to determine what impacts might result from any changes along these lines.

Is the Inspection Site Selection Process Truly Random, or Is There Some Inherent Bias?

Additionally, KDOT categorizes its roadways into five classes: Classes A through E. At one end of the spectrum, Class A roadways comprise the Interstate system, while Class E included minor short-distance roadways that carry low traffic volumes. The MQA inspection site selection process does not explicitly take roadway classification into account, and so it seems possible that in a given year if the inspection sites are overrepresented in one class or another the maintenance ratings could be skewed. Is there a need to include roadway classification in the site selection criteria?

Should There Be Some Change in the Way Inspection Sites Are Selected?

The inspection sites are selected by an algorithm that randomly select 30 investigation sites per maintenance subarea. As with any random procedure, there is almost surely going to be several subareas each year that appear to have a concentration of inspection sites on a few roads, with almost no inspection sites on other roads in the subarea. This naturally leads to questions by field personnel about why this is so. Additionally, there is concern that such a concentration could impact the overall maintenance rating for the state if it happened to fall on a roadway that recently had major rehabilitation versus a roadway that was in need of major rehabilitation. One method of avoiding this concentration of inspection sites is the use of a buffer area between sites. Would the inclusion of a buffer area have an impact on the statewide maintenance rating?

What Are the Trade-Offs to Changing the Number of Inspection Sites Per Subarea?

Determining the number of sites to be inspected per subarea involves a number of trade offs. For example, if the number of sites were increased it would be expected that the standard error of the estimated maintenance rating could be reduced, resulting in improved precision. However, this would mean that either more maintenance staff would need to be tasked with performing inspections, or the same number of staff would be required to spend a longer time conducting the inspections. Either way this would involve additional payroll expenses and would include the opportunity cost of other activities that would be left undone. Conversely, reducing the number of inspection sites would reduce the costs of collecting the MQA data and could free manpower resources that could be used for other maintenance activities, but could result in increasing the standard error of the estimate of the true maintenance rating. What are the expected statistical changes that could result from changing the sample size of the MQA data collection process?

MQA DATA COLLECTION AND ANALYSIS

In order to answer the questions posed in this research, it was necessary to develop a better understanding of the KDOT network. Answering the research questions would only be possible if more data were available; without a more complete picture of the state network no answers would be possible. This could best be accomplished in two ways: either collect the entire population of data or use the previously sampled inspection sites to create a model of the entire network. As it would be impractical to conduct an in-depth analysis of the entire 10,000-mi KDOT roadway network, it was decided to create a virtual model of the network and analyze it using Monte Carlo simulation.

Development of a Virtual State Roadway Network

The case of the MQA data for the state of Kansas is a good example of why modeling is used to solve complex problems: it is impractical, if not impossible, to know all of the various maintenance ratings on each element in each of over 100,000 possible inspection sites. Developing a model using average values was not practical, as each rated element is supposed to be given either a 0 or a 1; an average value (say 0.85 or 0.7) would make no sense in this context.

In order to accomplish this, a database of all possible inspection sites was created. Data from 2000 to 2007 (provided by KDOT) were entered into the database. Several simplifying assumptions had to be made in order to complete the population of this model of the state network.

- In order to include as much actual data as possible into the model, it was decided to include all available data from inspection years 2000 to 2007. In reality it would be expected that a site sampled in 2000 would no longer have the same rating simply due to the passage of time, natural aging of the facility that would take place, and annual maintenance activities to improve any deficiencies. However, with no viable method to discount the older values compared to the more current values, it was decided to simply include all data as given. Some locations were randomly selected to be inspected more than once during the 2000 to 2007 timeframe, and so in those instances only the most recent inspection results were used. It should be noted that the 1999 dataset was in a different format from the more recent data, and so was unusable for this research.

- KDOT does not maintain state routes that run through cities, and so these sections of the highway network are not selected as possible MQA inspection sites. As there was no easy way to remove these small sections they were left in the model. This resulted in a slight increase in the number of possible inspection sites in our model compared to what is available in the real MQA process.
- The KDOT MQA process does not inspect bridges, frontage roads, ramps, or segments under construction at the time of the inspection. Bridges are already inspected as part of another KDOT bridge inspection program; some possible inspection sites that fall entirely on long bridges are not included in the MQA program. Again, with no easy way to locate and remove such inspection sites, these were also left in the model, which resulted in a slight increase in modeled inspection sites.
- Some elements could be attributed to specific roadway sections, such as pavement type (rigid versus flexible) based on the actual inspections done on each roadway. But some relatively rare elements were not as easily attributed to specific roadways. For example, KDOT maintains some fencing along the edge of their right of way, but only a small percentage. Where they do it would to be in specific locations and not randomly distributed. Another consideration was that some elements tended to be concentrated in certain parts of Kansas; a good example is that types of under pavement drains varied by region due to soil and climatic variations. However, with no specific information on the geographic distribution of these types of elements, it was decided to simply distribute them statewide in a random fashion. While this provides a reasonable statewide representation of these elements, it may not appear realistic when viewing individual elements.

In the final result, the model developed included 108,247 possible inspection sites, which is slightly more than KDOT's number used in the past few years, as shown in Table 2. The total number of inspection sites that could have been selected varies slightly from year to year because sections of roadway that are under construction and also those sections that are maintained by cities (i.e., outside of KDOT maintenance activities) are removed from possible selection.

Out of these possible inspection sites and eliminating duplicate times when the same inspection sites were sampled, actual MQA data were available for 17,923 locations using the

TABLE 2 Comparison of Modeled Network Versus Actual KDOT MQA Network

Year	Total Possible Inspection Sites	No. of Inspection Sites That Met All Criteria
2006	114,619	91,560
2007	114,139	92,797
2008	112,275	89,440
Prepared model	108,247	108,247

2000 to 2007 data. This represented about 16.6% of the database, leaving 83.4% to be filled in with estimated data. In order to fill in all of the remaining inspection sites with estimated data, the following procedures were developed.

- The actual inspection data were reviewed for pavement type and shoulder type for all of the roadways in the state network. Each roadway was reviewed separately, and if it was determined that it was a flexible pavement then all of the possible inspection sites along that roadway were set as flexible pavements. When it was found that a roadway transitioned from flexible to rigid pavement (or vice versa) there was almost always several inspection sites between the last known inspection site of flexible pavement and the first known inspection site for rigid pavements. The inspection sites between these were split evenly to reflect the closest known sites. The same process was conducted for the shoulder category.
- The presence of specific elements was allocated throughout the virtual network to reflect the same presence proportions of the actual known inspection data. For example, only about 36% of all inspected locations had warning or regulatory signing. So when the rest of the virtual network was filled in this proportion was kept so that only 36% of the virtual network would have warning or regulatory signing present.
- For each applicable maintenance element, a pass (1) or a fail (0) was assigned according to an algorithm that kept the statewide proportion of passes and failures the same as the known data. For example, if 75% of the actual inspection sites had received a passing rating for the condition of their culverts, then the algorithm randomly allocated passes and failures throughout the remainder of the network so that the entire network also had a 75% pass rate.

This resulted in a virtual roadway network of the state of Kansas with all of the MQA data completed for all 108,247 possible inspection sites. With this necessary step completed it was then possible to use the Monte Carlo simulation method to examine the research questions related to the statistical validity of the KDOT MQA program.

Monte Carlo Simulation Methods

In the 1930s and 1940s computational methods had developed enough to allow large quantities of data to be generated and studied, allowing complex models to be built and used in a wide variety of fields including mathematics and physics. The natural problem for many models was that it was not possible to gain perfect knowledge of the system being studied, i.e., only a sampling of data were available and they needed to be used to estimate the population. To provide statistical power during these times when deterministic approaches were insufficient, Monte Carlo methods were developed (*4*). Monte Carlo methods allow the generation of large samples of simulated data by taking the distribution of known empirical data—actual samples that were collected—and using that distribution to fill in the remainder of the unsampled population. The result is a model of the population with some actual data and some virtual estimated data. These methods tend to be used when it is infeasible or impossible to compute an exact result with a deterministic algorithm (*5*).

The basic principle in Monte Carlo simulation lies in the observation of behavior of statistic when random samples are drawn. In order to achieve a pseudo population an artificial world is created. It resembles the data drawn from the true population. Then multiple trials are conducted on the pseudo population to investigate the behavior of the procedure across the samples. The basic procedure is

1. Develop a computer algorithm to generate a pseudo population in specified manner.
2. Apply specific sampling procedures to reflect the statistical situation.
3. Calculate the estimator for the pseudo sample.
4. Repeat the above two steps *t* times, where *t* is number of trials.
5. Then, a relative frequency distribution is created to determine the pattern followed by the statistic.

It often is very difficult to predict how a variable is distributed in the real world. Moreover it is important to generate proper random variables for constructing the Monte Carlo simulation. In order to understand the distribution the random variable must be defined first. A random variable can be viewed as a realization of some event that can take on a range of values, with the probability of each of these values occurring being determined by the variable's distribution function, $F(x)$. The most studied probability density function is the normal or Gaussian distribution function. If $F(x)$ takes the form of a normal (Gaussian) distribution the standard normal variable can be expressed as:

$$F(x) = P(X \le x) = \left(\frac{1}{\sqrt{2\pi}}\right)\int_{-\infty}^{x} e^{-\frac{x^2}{2}}\,dx \tag{1}$$

So with the created model, it was possible to apply Monte Carlo simulation to run many thousands of trials to test each of the research questions. Because each trial would randomly select the specified number of inspection sites from the network, each trial would be expected to be slightly different, and result in slightly different maintenance ratings. It is the distributions of the maintenance ratings that result from 10,000 trials that were analyzed for this research.

FINDINGS

Is the Sample Selection Process Truly Random, or Is There Some Inherent Bias?

One of the research questions studied was whether the existing MQA program adequately captured a representative sample of each class of roadway in the state network. This was an important question, because if one class were over- or underrepresented any maintenance effort focused on a specific classification might have a disproportionate impact on the MQA maintenance ratings. Using the Monte Carlo simulation method, 10,000 different trials were simulated where the full 3,360 inspection sites were selected. At the conclusion of the 10,000 trials, the lowest, mean, and highest percentages selected for each roadway classification were selected. Additionally, the 2.5th-percentile and the 97.5th-percentile percentages were also selected. These are analogous to the 95% confidence interval; 95% of all values fall between these values.

The results for each roadway classification are shown in Table 3. It should be noted that the values in each percentile distribution occurred independently for each roadway classification, so while Class A roadways were found to have a lowest rating of 11%, this almost certainly did not happen in the same Monte Carlo simulation trial as the lowest rating for the other roadway classifications.

It was interesting to note, however, that the differences between the true percentages of each roadway classification were very close to the true percentage of inspection sites in the model. In fact, the largest difference observed was for Class B roadways, where the percentage in the model was 21.2% and the lowest sampled percentage was 18%, a difference of 3.2%. In 95% of the trials it was found that differences were in the range of only 1% to 2% or less. These small differences overall are a good indication that indeed the MQA process does a good job of sampling the different roadway classifications adequately, and so no changes appear to be needed in this regard.

Should There Be Some Change in the Way Inspection Sites Are Selected?

Another area of interest for this research was what impact on the maintenance ratings would result from including a buffer area during the selection process. In order to assess this question, all 112 subareas were ranked from those with the most roadway miles to those with the fewest. Three subareas were selected: the subarea with the most number of roadway miles, one with a typical number, and one with the fewest. This selection process is shown in Figure 2. Monte Carlo simulation was used to evaluate the ability of the KDOT MQA selection algorithm to select 30 inspection sites per subarea with various buffer distances assigned; 10,000 Monte Carlo simulation trials were conducted for buffer distances from 0 to 4 mi in 0.5-mi increments; the goal was to determine when 30 inspection sites could not reliably be selected without violating the buffer. For the subarea with the largest number of roadway miles it was possible to reliably select 30 inspection sites even when the buffer area was 4 mi long. For the subarea with a typical amount of roadway miles the model could no longer reliably select 30 inspection sites once the buffer area reached 1.5 mi, and for the smallest subarea this occurred at only 0.5 mi.

This means that if even a 0.5-mi buffer were incorporated into the system there would be a risk that at least for the smallest subareas that for a given year 30 inspection sites might not be

TABLE 3 Distribution of Sampled Roadway Classification After 10,000 Monte Carlo Simulation Runs

Roadway Classification	Total Inspection Sites in Model	Percent of Total Model	Distributions of Sampled Roadway Classification after 10,000 Runs				
			Lowest (%)	2.5th Percentile	Mean (%)	97.5th Percentile	Highest (%)
A	13,071	12.1	11	12	12	13	14
B	22,899	21.2	18	19	20	21	22
C	23,968	22.1	19	21	22	23	24
D	31,082	28.7	26	27	28	29	31
E	17,227	15.9	13	14	15	16	17
Total	108,247	100.0					

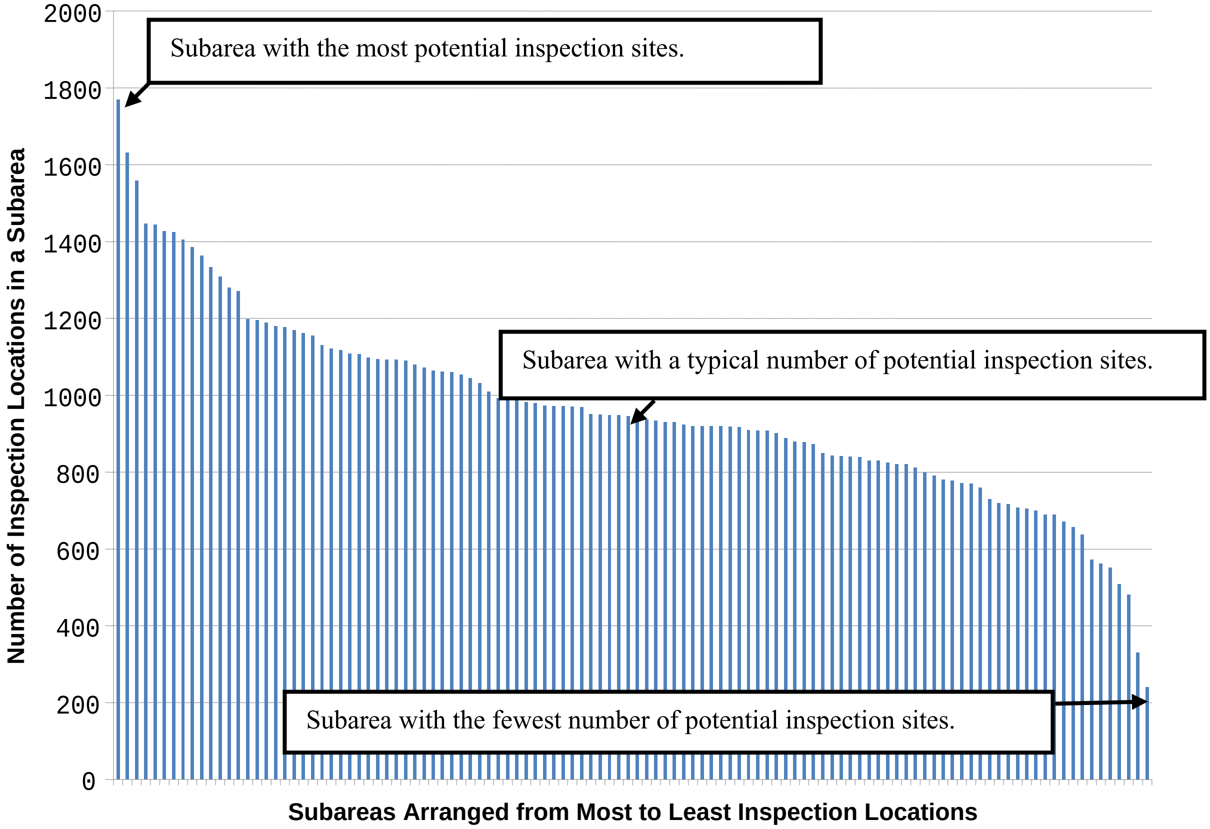

FIGURE 2 Number of inspection sites in each subarea; three subareas selected for further analysis identified.

able to be selected without violating the established buffer. While it would have been interesting to have determined how the maintenance ratings would have changed with the buffers, that analysis would be meaningless in light of the potential of the selection problems discussed above.

Therefore, it was concluded that a buffer should be avoided by KDOT in their current selection scheme. If a buffer was considered essential KDOT would have to either allow an occasional violation of their buffer rules, or would have to fundamentally change the selection algorithm away from selection by subarea and move to a larger geographic unit, such as by district or statewide.

What Are the Trade-Offs to Changing the Number of Inspection Sites per Subarea?

The final research interest that was studied with Monte Carlo simulation was the impact on maintenance ratings by changing the number of inspection sites sampled per subarea. Using Monte Carlo simulation 10,000 trials were conducted for each of three different levels of sampling: 15 inspection sites per subarea, 30 inspection sites per subarea (the current KDOT sampling rate), and 60 inspection sites per subarea. The results are shown in Tables 4 through 6.

TABLE 4 Statistical Distributions for Each MQA Element with 15 Inspection Sites per Subarea

			Minimum	2.5th Percentile	Mean	97.5th Percentile	Maximum
Travelway		**Overall maintenance rating**	**96.0**	**96.5**	**96.9**	**97.3**	**97.8**
	Flexible	Potholes	99.0	99.0	99.7	100.0	100.0
		Cracking	86.0	98.0	89.3	91.0	92.0
		Rutting	98.0	99.0	99.1	100.0	100.0
		Deformation	99.0	99.0	100.0	100.0	100.0
	Rigid	Potholes	91.0	94.0	96.4	98.0	100.0
		Cracking	88.0	91.0	94.2	97.0	99.0
		Faulting	97.0	98.0	99.6	100.0	100.0
		Joint sealant	90.0	93.0	96.1	98.0	100.0
Shoulder		**Overall maintenance rating**	**89.5**	**90.1**	**91.0**	**91.8**	**92.4**
	Paved	Joint separation	91.0	93.0	95.0	97.0	98.0
		Cracking	84.0	86.0	88.7	91.0	93.0
		Edge drop off	95.0	96.0	97.4	99.0	99.0
		Deformation	98.0	98.0	99.2	100.0	100.0
	Unpaved	Edge ruts	76.0	78.0	80.8	83.0	86.0
		Drainage	92.0	94.0	95.3	97.0	98.0
		Vegetation	81.0	83.0	85.8	88.0	90.0
Roadside		**Overall maintenance rating**	**87.6**	**88.3**	**89.1**	**89.8**	**90.4**
		Vegetation–weeds	85.0	87.0	88.1	90.0	91.0
		Litter	94.0	95.0	95.9	97.0	98.0
		Fencing	92.0	94.0	96.4	98.0	100.0
		Brush–trees	98.0	99.0	99.1	100.0	100.0
		Slope erosion	78.0	80.0	81.9	84.0	85.0
		Side road entrances	72.0	75.0	78.0	81.0	84.0
Drainage		**Overall maintenance rating**	**83.5**	**84.9**	**86.1**	**87.4**	**88.9**
		Curb and gutter	49.0	63.0	75.2	86.0	93.0
		Ditch	91.0	92.0	93.1	94.0	95.0
		Erosion control devices	81.0	87.0	90.9	95.0	97.0
		Culvert pipes	69.0	72.0	75.3	78.0	81.0
		Edge under drains	42.0	50.0	59.1	68.0	74.0
		Inlets	82.0	88.0	92.8	97.0	100.0
Traffic guidance		**Overall maintenance rating**	**83.9**	**85.5**	**86.7**	**87.9**	**88.8**
		Warning–regulatory signing	64.0	67.0	70.6	74.0	78.0
		Other signing	67.0	71.0	74.5	78.0	82.0
		Guard attenuators–barriers	51.0	62.0	75.0	87.0	98.0
		Pavement markings	96.0	96.0	97.3	98.0	99.0
Overall maintenance rating			**90.4**	**90.9**	**91.2**	**91.4**	**91.9**

TABLE 5 Statistical Distributions for Each MQA Element with 30 Inspection Sites per Subarea

			Minimum	2.5th Percentile	Mean	97.5th Percentile	Maximum
Travelway		**Overall maintenance rating**	**96.3**	**96.6**	**96.9**	**97.2**	**97.4**
	Flexible	Potholes	99.0	99.0	99.7	100.0	100.0
		Cracking	87.0	88.0	89.3	90.0	91.0
		Rutting	99.0	99.0	99.0	99.0	100.0
		Deformation	99.0	100.0	100.0	100.0	100.0
	Rigid	Potholes	92.0	95.0	96.4	98.0	99.0
		Cracking	90.0	92.0	94.3	96.0	97.0
		Faulting	98.0	99.0	99.5	100.0	100.0
		Joint sealant	93.0	94.0	96.1	98.0	99.0
Shoulder		**Overall maintenance rating**	**89.8**	**90.4**	**91.0**	**91.5**	**92.3**
	Paved	Joint separation	93.0	94.0	95.1	96.0	97.0
		Cracking	86.0	87.0	88.7	90.0	92.0
		Edge drop off	95.0	96.0	97.4	98.0	99.0
		Deformation	98.0	99.0	99.2	100.0	100.0
	Unpaved	Edge ruts	77.0	79.0	80.8	83.0	84.0
		Drainage	93.0	94.0	95.3	96.0	97.0
		Vegetation	82.0	84.0	85.8	87.0	89.0
Roadside		**Overall maintenance rating**	**88.2**	**88.5**	**89.1**	**89.6**	**90.1**
		Vegetation–weeds	86.0	87.0	88.1	89.0	90.0
		Litter	95.0	95.0	95.9	97.0	97.0
		Fencing	93.0	95.0	96.4	98.0	99.0
		Brush–trees	99.0	99.0	99.0	99.0	100.0
		Slope erosion	79.0	81.0	81.8	83.0	85.0
		Side road entrances	74.0	76.0	78.0	80.0	82.0
Drainage		**Overall maintenance rating**	**84.3**	**85.3**	**86.1**	**87.0**	**87.8**
		Curb and gutter	59.0	67.0	75.2	83.0	88.0
		Ditch	92.0	92.0	93.1	94.0	95.0
		Erosion control devices	85.0	88.0	90.9	94.0	96.0
		Culvert pipes	71.0	73.0	75.3	77.0	80.0
		Edge under drains	48.0	53.0	59.0	65.0	71.0
		Inlets	86.0	90.0	92.8	96.0	98.0
Traffic guidance		**Overall maintenance rating**	**84.7**	**85.9**	**86.7**	**87.6**	**88.4**
		Warning–regulatory signing	66.0	68.0	70.6	73.0	75.0
		Other signing	70.0	72.0	74.4	77.0	79.0
		Guard attenuators–barriers	53.0	66.0	75.0	83.0	89.0
		Pavement markings	96.0	97.0	97.2	98.0	98.0
Overall maintenance rating			**90.6**	**90.9**	**91.2**	**91.4**	**91.7**

TABLE 6 Statistical Distributions for Each MQA Element with 60 Inspection Sites per Subarea

			Minimum	2.5th Percentile	Mean	97.5th Percentile	Maximum
Travelway		**Overall maintenance rating**	**96.5**	**96.7**	**96.9**	**97.1**	**97.3**
	Flexible	Potholes	99.0	99.0	99.7	100.0	100.0
		Cracking	88.0	89.0	89.3	90.0	91.0
		Rutting	99.0	99.0	99.0	99.0	100.0
		Deformation	99.0	100.0	100.0	100.0	100.0
	Rigid	Potholes	94.0	95.0	96.4	97.0	98.0
		Cracking	91.0	93.0	94.3	96.0	97.0
		Faulting	98.0	99.0	99.4	100.0	100.0
		Joint sealant	93.0	95.0	96.1	97.0	98.0
Shoulder		**Overall maintenance rating**	**90.1**	**90.5**	**90.9**	**91.3**	**91.7**
	Paved	Joint separation	93.0	94.0	95.1	96.0	97.0
		Cracking	86.0	87.0	88.7	90.0	91.0
		Edge drop off	96.0	97.0	97.4	98.0	98.0
		Deformation	99.0	99.0	99.1	100.0	100.0
	Unpaved	Edge ruts	78.0	80.0	80.8	82.0	83.0
		Drainage	94.0	95.0	95.3	96.0	96.0
		Vegetation	84.0	85.0	85.8	87.0	88.0
Roadside		**Overall maintenance rating**	**88.3**	**88.7**	**89.1**	**89.4**	**89.7**
		Vegetation–weeds	87.0	87.0	88.1	89.0	89.0
		Litter	95.0	95.0	96.0	96.0	97.0
		Fencing	94.0	95.0	96.4	97.0	98.0
		Brush–trees	99.0	99.0	99.0	100.0	100.0
		Slope erosion	80.0	81.0	81.8	84.0	84.0
		Side road entrances	75.0	75.0	78.0	80.0	81.0
Drainage		**Overall maintenance rating**	**84.9**	**85.4**	**86.1**	**86.8**	**87.2**
		Curb and gutter	65.0	69.0	75.1	80.0	85.0
		Ditch	92.0	93.0	93.1	94.0	94.0
		Erosion control devices	87.0	89.0	90.9	93.0	94.0
		Culvert pipes	72.0	74.0	75.3	77.0	78.0
		Edge under drains	51.0	55.0	59.0	63.0	69.0
		Inlets	88.0	91.0	92.9	95.0	96.0
Traffic guidance		**Overall maintenance rating**	**85.6**	**86.1**	**86.7**	**87.3**	**87.8**
		Warning–regulatory signing	67.0	69.0	70.6	72.0	74.0
		Other signing	71.0	73.0	74.5	76.0	78.0
		Guard attenuators–barriers	63.0	69.0	74.9	81.0	85.0
		Pavement markings	97.0	97.0	97.1	98.0	98.0
Overall maintenance rating			**90.8**	**91.0**	**91.2**	**91.4**	**91.5**

Again a review of the trials were examined, and the lowest, 2.5th percentile, mean, 97.5th percentile, and the highest value were determined for each MQA element as well as the overall maintenance ratings. Overall it can be seen by comparing the three tables that there was little variation in values between the 15-, 30-, and 60-inspection site strategies for the overall maintenance ratings as well as the maintenance ratings for each of the main sections (travelway, shoulder, etc.).

In terms of the statewide overall maintenance rating, as well as the individual sections' maintenance ratings, there were only small changes as the number of inspection sites were changed. For example, the lowest and highest statewide maintenance rating varied as follows:

- 90.4 to 91.9 when 15 inspection sites per subarea were selected;
- 90.6 to 91.7 when 30 inspection sites per subarea were selected; and
- 90.8 to 91.5 when 60 inspection sites per subarea were selected.

This compares well with the overall maintenance rating of 91.1 which would be achieved if all 108,247 inspection sites possible in the model were sampled.

Even many of the individual elements do not show much variation, at least as long as there were many inspection sites that contained the element. There were several relatively rare elements—such as curb and gutter, edge and under drains, and guard attenuators–barriers—where the variation was much larger.

Overall there seems little to be gained from a statistical standpoint from increasing the sample size, at least for the overall maintenance ratings. If the only measure of interest to KDOT are the overall maintenance ratings there may be some financial advantage gained to lowering the required inspection sites from 30 to some lower number per subarea. More research would be needed to determine an appropriate level. However, if KDOT desires to use the maintenance rating for analyzing individual elements, reducing the number of inspection sites may be detrimental, especially for relatively rare elements. However, even doubling the number of inspection sites to 60 still leaves room for wide variations for the relatively rare elements, so using MQA data to analyze individual elements should be conducted with caution regardless of the number of inspection sites selected.

FUTURE RESEARCH NEEDS

There were several simplifying assumptions that were made in the creation of the statewide network model. For example, when the model was created any uninspected locations in the model were populated with estimated data and randomly distributed statewide without regard for the roadway classification. If there is a quality difference in some attributes between classifications, then this process may have oversimplified the completed model. A more refined approach could be to allocate the estimated data separately for each roadway classification, which should result in a more accurate model overall.

There are several unanswered questions regarding ways that the KDOT MQA could be modified. One question raised by KDOT pertained to the examination of rare elements such as certain drainage structures only found in certain areas of the state. As the process used to populate the model assigned elements across the virtual network randomly, elements that were concentrated in certain areas of the state were not correctly represented. If the model population process was modified so that individual elements were allocated randomly based on smaller geographic areas (such as districts, areas, or subareas) it might be possible to further increase the validity of the results of individual elements.

Finally, there have been questions raised regarding the ability of the MQA data collection to evaluate locations smaller than the state level. For example, could the MQA data be used to evaluate the maintenance efficacy of on district, area, or even subarea compared to others? Because the algorithm used to populate the virtual network did not account for these geographic boundaries this was a question that could not be adequately researched. However, if the algorithm were updated to fill in inspection sites with data representative to the geographic unit in question (district, area, subarea) then this distinction could be made. However, as with any statistical procedure, the results should be used with caution due to the reduction in sample size.

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MAINTENANCE QUALITY ASSURANCE

Development of a Comprehensive Framework for the Efficiency Measurement of Road Maintenance Strategies Using Data Envelopment Analysis

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This paper presents a comprehensive framework that can measure the overall efficiency of road maintenance operations and that can also consider the effects of external and uncontrollable factors (such as climate, traffic, etc.) on such overall efficiency. This efficiency measurement framework, when implemented, identifies: (*a*) the relative efficiency of different units in performing road maintenance services, (*b*) the benchmarks (peers) and targets that pertain to the inefficient units (in an effort to inform the decision-makers within such units of possible efficiency improvements than can be secured in the future), (*c*) the fundamental relationships between the maintenance levels of service and the budget requirements, (*d*) the effects of the environmental and operational factors on the road maintenance efficiency of units. It is important to note that items *a* and *c*, as listed above, relate to the maintenance management issues identified by TRB as "in need of comprehensive investigation" in 2006. The findings of the research outlined herein contributes new knowledge to the maintenance management field in the road infrastructure domain by providing a framework that is able to differentiate effective and efficient maintenance strategies from effective and inefficient ones; as such, the impact of such framework is broad, significant, and relevant to the decision-making process performed by the maintenance managers.

Within the last two decades, the preservation of the road infrastructure has been gaining a lot of attention. In 1988, a survey performed on about 10% of all U.S. infrastructure by the National Council on Public Works Improvement (as appointed by the president of United States) revealed that the nation's roads were in better than fair condition. A number of similar surveys were performed by ASCE in 1998, 2001, 2003, and 2005. According to the most recent survey performed in 2005, the nation's roads are in poor condition; indicating a severe deterioration over the last two decades (*1*).

This has brought about institutional changes, predominant of which is the challenge for the state departments of transportation (DOTs) to achieve maximum performance in their road maintenance efforts (*2*). Such challenge makes it imperative to implement comprehensive systems that measure road maintenance performance. Therefore, maintenance managers should be provided with the mechanisms that allow for the measurement and analysis of maintenance performance, that assure that maximum performance is achieved, and that facilitate the realization of improvements, changes, and decisions (such as choosing between private contractors and in-house forces to perform maintenance) (*2*).

SIGNIFICANCE OF THE PROBLEM AND PURPOSE OF THE RESEARCH

As pointed out by TRB in 2006, even though the road maintenance performance measurement systems developed and implemented by the state DOTs elaborate on the maintenance level of service (LOS) (i.e., effectiveness of the road maintenance), the fundamental relationships between the maintenance LOS and the budget requirements (i.e., efficiency of road maintenance) need more investigation (*2*).

For the purposes of this paper, effectiveness can be defined as the degree to which an output (product–service) conforms to the requirements. Efficiency, on the other hand, is the degree to which the process produces the output (product–service) at a minimum resource level (*3*). In other words, effectiveness can be stated as "doing the right things" and efficiency can be stated as "doing the things right" (*4*). Efficiency is an essential performance measurement dimension. As a matter of fact, Sink and Morris define performance as an "integrated relationship among seven dimensions: effectiveness, efficiency …" (*5*).

Road users, as tax payers, expect not only a well-maintained road system, but also require it to be efficiently maintained (*6*). Moreover, given the proliferation of the asset management concept that calls for the delivery of effective and efficient services to the community (*7*), measuring only effectiveness and disregarding efficiency is an incomplete approach to performance assessment. Not knowing how efficient state DOTs are in being effective can lead to excessive and unrealistic maintenance budget expectations. Given this, there is a need to develop and implement a comprehensive framework that can measure the overall efficiency of road maintenance operations.

This research develops and implements a comprehensive framework that can measure the overall efficiency of road maintenance operations and that can also consider the effects of external and uncontrollable factors (such as climate, traffic, etc.) on such overall efficiency. This efficiency measurement framework, when implemented, identifies: (*a*) the relative efficiency of different units in performing road maintenance services, (*b*) the benchmarks (peers) and targets that pertain to the inefficient units (in an effort to inform the decision makers within such units of possible efficiency improvements than can be secured in the future), (*c*) the fundamental relationships between the maintenance levels of service and the budget requirements, (*d*) the effects of the environmental and operational factors on the road maintenance efficiency of units. It is important to note that items *b* and *c*, as listed above, relate to the maintenance management issues identified by TRB as in need of comprehensive investigation in 2006 (*2*).

The purpose of this paper is to introduce the developed road maintenance efficiency measurement framework and the main approach [data envelopment analysis (DEA)] that was used to develop such framework.

DATA ENVELOPMENT ANALYSIS

A commonly used measure of efficiency (*8*) is

$$\text{Efficiency} = \text{Output}/\text{Input} \tag{1}$$

This measure is often inadequate due to the existence of multiple inputs and outputs in complex processes. Given the fact that there are many inputs used by, and outputs obtained as a result of, the road maintenance process, the efficiency framework needs to incorporate all inputs and outputs to be able to identify the overall efficiency of a given unit's road maintenance process. Also, since there are many external and uncontrollable factors that affect the road maintenance performance, such framework needs to incorporate all factors to provide leveled comparison for different units trying to maintain roads facing different circumstances. However, it is challenging to measure the overall efficiency of a process when such process is a multiple input–multiple output process and when such process is affected by multiple external and uncontrollable factors.

To be able to develop the efficiency measurement framework, the authors have identified a number of approaches as possible candidates that may address both of the issues identified above. However, all but one approach have fallen short of addressing the challenges of this research as well as tackling the complex nature of the process (i.e., road maintenance) that is scrutinized in this research. Thus, the authors chose the only remaining approach, DEA, as the approach to utilize to develop the maintenance efficiency measurement framework.

DEA is a mathematical method based on production theory and the principles of linear programming. It enables one to assess how efficiently a firm, organization, agency, or such other unit uses the resources available (inputs) to generate a set of outputs relative to other units in the data set *(9,10)*. Within the context of DEA, such units are called decision making units (DMUs). A DMU is said to be efficient if the ratio of its weighted outputs to its weighted inputs is larger than the similar ratio for every other DMU in the sample (*10*). The weights for the inputs and outputs do not need to be identified by the decision maker and instead are determined and optimized by the DEA model in the best interest of DMUs (*11*). The selection of the weights is only subject to limitations that they should be nonnegative and they cannot result in an efficiency score larger than 100% (*11,12*).

The main idea of DEA is to construct a frontier of efficient DMUs representing the best practices. DMUs located on such frontier (i.e., efficient frontier) act as the benchmarks (peers) for the inefficient DMUs in the data set. The challenge is to find the position of the efficient frontier and then compute the distance from it to each inefficient DMU to identify the efficiency score of such DMU. The efficiency score is constrained to the interval of 0% to 100% (*13*).

Figure 1 presents the application of DEA for a process with two inputs and a single output. For example, let's assume that the process under investigation is the road paving operation. The inputs of the process are: (*a*) the number of paving crews (x_1) and (*b*) the time spent in days for the paving operation (x_2). The output of the process is lane miles of road paved (y). The DMUs (e.g., different contractors undertaking this paving operation) shown in dots, are plotted on an x–y plane by using the values for their inputs (x_1 and x_2) and output (y). Then, the efficient frontier, containing the DMUs with 100% efficiency score (relative to the other DMUs in the data set), is drawn by identifying the efficient pairs. Efficient pairs are identified by picking adjacent pairs of DMUs and connecting them with a line segment. If the line segment has a non-positive slope and none of the other DMUs lies between such line segment and the origin, then chosen DMUs are stated to be efficient and otherwise they are stated to be inefficient (*14*). Hence, according to Figure 1, DMUs represented by "E," "D," "C," and "F" have an efficiency score of 100%, and DMUs represented by "A" and "B" have efficiency scores that are between 0% and 100%. The efficiency score for any inefficient DMU can be calculated by measuring its relative distance from the efficient frontier. For example, the efficiency score of DMU B can be identified to be 63% by computing the ratio of $|OB'|$ to $|OB|$ as shown in Figure 1. It is important to note that DEA not only identifies the efficiency score for each DMU but also

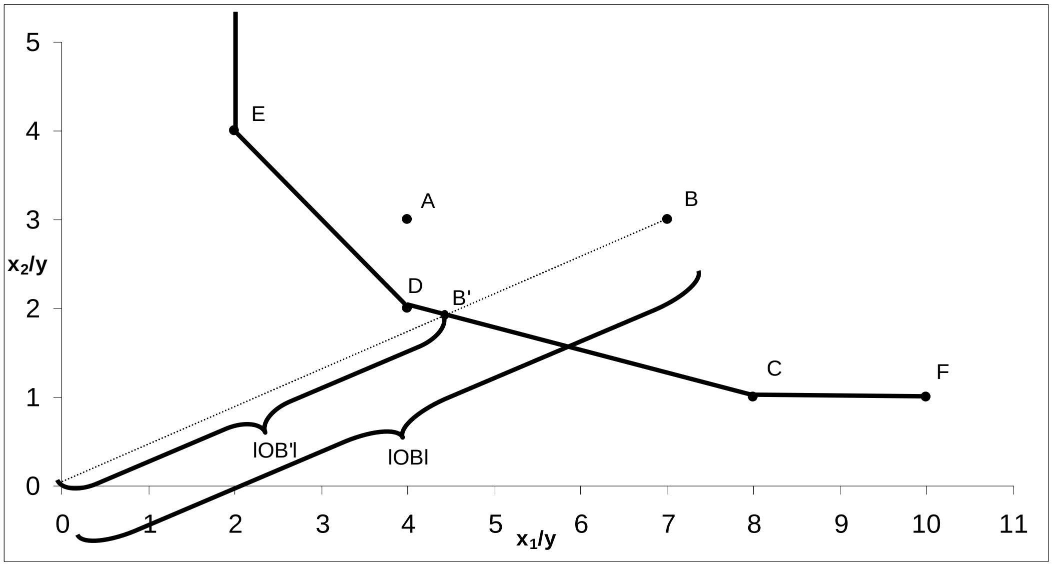

FIGURE 1 DEA model for a process with two inputs and a single output (*8*).

identifies the peer DMUs for inefficient DMUs. For the example presented in Figure 1, the peer DMUs for DMU B can be identified as DMU C and DMU D as the projection of DMU B on the efficient frontier, B′, is a weighted combination of such peer DMUs. As can be understood, DEA is a relative efficiency calculation technique as efficient frontier is not absolute but determined by the data set under investigation.

Within DEA, the efficiency score of any DMU, as proposed by Charnes et al. (*15*), is calculated as the maximum of a ratio of the weighted outputs to weighted inputs subject to the constraints that (*a*) the similar ratio for every DMU in the data set be less than or equal to unity using the same set of weights and (*b*) such weights be nonnegative (*15*). The linear programming formulation possessing such constraints is presented in the formulation below (*15*). Such formulation ensures that the calculated efficiencies are relative to the best performing DMU (or DMUs if there is more than one best performing DMU). The best-performing DMU is given an efficiency score of 100%, and the efficiencies of other DMUs vary, between 0% and 100%, relative to this best performance (*9*).

$$\text{maximize } Q_0 = \frac{\sum_{r=1}^{s} u_r y_{ro}}{\sum_{i=1}^{m} v_i x_{i0}} \tag{2}$$

subject to

$$\frac{\sum_{r=1}^{s} u_r y_{rj}}{\sum_{i=1}^{m} v_i x_{ij}} \leq 1 \ ; j = 1,\ldots, n; r = 1,\ldots, s; i = 1,\ldots, m \tag{3}$$

$$u_r, v_i \geq 0 \tag{4}$$

where

Q_0 = the efficiency score of the DMU that is under consideration. Its value ranges between 0% and 100%;
n = number of DMUs in the data set;
s = number of outputs;
m = number of inputs;
y_{rj}, x_{ij} = known outputs and inputs of the jth DMU and they are all positive; and
$u_r, v_i \geq 0$ = the variables' (outputs' and inputs') weights to be determined by the solution of this optimization problem.

The model presented above, in essence, seeks the weights (u_r) for each output and weights (v_i) for each input of the DMU under investigation that maximize the efficiency score of that DMU, subject to the constraint that such weights, when applied to the output-to-input ratios for all other DMUs in the data set (including the DMU under investigation), result in an efficiency score which is equal to or less than 1. The efficiency score and the weights of the input and output variables for each DMU can be calculated by solving the linear program formulation presented above for each DMU in the data set. The weights calculated are DMU-specific and due to the optimization structure of the linear program formulation as described above, such weights are determined by the linear program for each DMU (as allowed by the constraints) to maximize its efficiency score.

The efficiency score mentioned above is called the input reducing efficiency within the context of DEA. It indicates the level by which the inputs utilized by an inefficient DMU can be reduced without changing the level of outputs produced by such DMU. In DEA, efficiency can be studied from an output point of view as well as from an input point of view. Therefore, DEA also establishes the output increasing efficiency, which is defined as the level by which the outputs produced by an inefficient DMU can be increased without changing the level by which inputs are utilized by such DMU (*14*).

STRENGTHS AND LIMITATIONS OF DATA ENVELOPMENT ANALYSIS

The DEA approach possesses the following strengths (*9, 16, 17*):

- DEA can simultaneously deal with multiple outputs and multiple inputs each of which may be measured in its own natural physical unit;
- DEA has the capability to consider external and uncontrollable factors while measuring the overall efficiency of DMUs;
- DEA focuses on the best-practice frontiers rather than the central tendency frontiers (as obtained through regression analyses); and
- DEA is nonparametric and thus does not require the specification of an explicit functional form relating inputs to outputs.

The most important limitations of DEA are as follows (*9,16,17*):

- Application of DEA requires a separate linear program be solved for each DMU in the data set. When there are many DMUs, the computation can be cumbersome. Nonetheless, this limitation has been minimized with the development of computer software that specifically deals with DEA problems.
- Since DEA is an extreme point technique, errors in measurement or recording of data for input-output variables may result in significant problems. Thus, utmost care should be given to assure that input-output data is accurate.
- As efficiency scores in DEA are obtained by running a series of linear program formulations, it becomes intuitively difficult to explain the process of DEA to the nontechnical audience or decision makers for the cases in which there are more than two inputs and outputs. An audience that does not have background in linear programming may not deem DEA as transparent and may find it difficult to comprehend its results. Nonetheless, this issue may be overcome by explaining the DEA process in simpler terms and by proper use of charts and tables to communicate the results.
- DEA cannot deal with qualitative variables. Such variables need to be assigned numerical values to be used in the mathematical evaluation of efficiency as used in DEA. The common practice to perform this is to find some measurable surrogate variable which possesses a known relation to the varying levels of the qualitative variable.

ROAD MAINTENANCE EFFICIENCY MEASUREMENT FRAMEWORK

The DEA-based road maintenance efficiency measurement framework developed by the authors is depicted in Figure 2. This framework is composed of eight components. Each component identifies the best alternative possible given the different scenarios for which the framework is implemented. Such different scenarios relate to: (*a*) the different units of comparison, (*b*) availability of data in different degrees, and (*c*) different models utilized as a part of the DEA approach. A brief discussion of each component follows. The reader is referred to the work by Ozbek (*18*) which provides a comprehensive discussion on the DEA-based road maintenance efficiency framework.

Component 1: Developing the Comprehensive List of Input–Output Variables and Uncontrollable Factors

This component calls for the development of the comprehensive list of input–output variables and uncontrollable factors pertinent to the process under investigation. As an example, such a list for the bridge maintenance process, along with the explanations or metrics for each of the input-output variables and uncontrollable factors is presented in Table 1. As can be seen in such list, the uncontrollable factors for the bridge maintenance process can be divided into two categories: (*a*) uncontrollable factors that affect the deterioration of bridges and (*b*) uncontrollable factors that affect maintenance efforts.

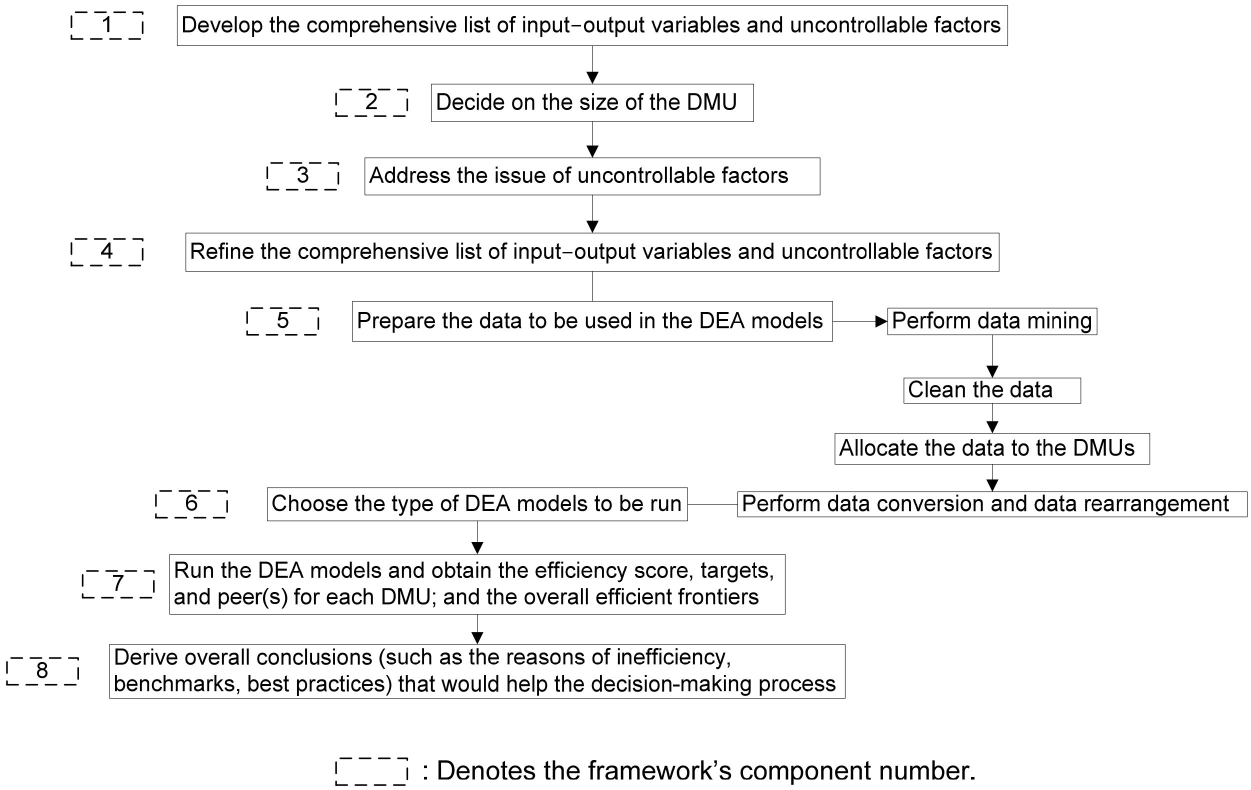

FIGURE 2 Components of the developed DEA road maintenance efficiency framework.

TABLE 1 Comprehensive List of Input–Output Variables and Uncontrollable Factors Pertinent to the Maintenance of Bridges

Variable Name		**Variable Explanation or Metric**
Input Variables and Uncontrollable Factors	Cost for maintaining the bridges	Dollars
	Climate: effect on deterioration of the bridges	Yearly temperature cycles (Δ temperature), number of yearly freeze–thaw cycles
	Climate: effect on maintenance efforts performed for meeting level-of-service requirements for the bridges (productivity–availability of crews)	Yearly precipitation amounts (inches)
	Traffic: effect on deterioration of the bridges	Equivalent Single Axle Load (ESAL)
	Traffic: effect on maintenance efforts performed for meeting level-of-service requirements for the bridges (productivity–availability of crews)	Average daily traffic (ADT)
	Snow treatment: effect on deterioration of the bridges	Count (of chloride applications)

(continued on next page)

TABLE 1 (*continued*) **Comprehensive List of Input–Output Variables and Uncontrollable Factors Pertinent to the Maintenance of Bridges**

Variable Name		**Variable Explanation or Metric**
Input Variables and Uncontrollable Factors	Speed limit: effect on deterioration of the bridge	Miles per hour
	Accidents damaging bridges: effect on deterioration of the bridges	Count (of accidents damaging bridges) per year
	Subsurface conditions: effect on deterioration of the bridges	Good, poor, rock soil, water table, etc. (give a grade based on effect)
	Thickness of the deck: effect on deterioration of the bridges	Inches
	Type of paved lanes: effect on deterioration of the bridges	Concrete, asphalt (give a grade based on the effect)
	Type of paved lanes: effect on maintenance efforts performed for meeting level-of-service requirements for the bridges (productivity of crews)	Concrete, asphalt (give a grade based on the effect)
	Span information: effect on deterioration of the bridges	Span length, span type, etc.
	Age of bridges: effect on deterioration of the bridges	Years
	Location: effect on deterioration of the bridges	Above a creek, major river, highway, railroad, etc. (give a grade based on effect)
	Location: effect on maintenance efforts performed for meeting LOS requirements for the bridges (productivity of crews)	Above a creek, major river, highway, railroad, etc. (give a grade based on effect)
	Terrain: effect on deterioration of the bridges	Slope, elevation, and orientation
	Terrain: effect on maintenance efforts performed for meeting LOS requirements for the bridges (productivity of crews)	Slope, elevation, and orientation
	Total area served: effect on maintenance efforts performed for meeting LOS requirements for the bridges (productivity of crews)	Sum of the area (deck length × deck width) of all of the bridges within the DMU
Output Variables	Change in the condition of the deck of the bridge	Deck rating_{t1} – deck rating_{t0}
	Change in the condition of the superstructure of the bridge	Superstructure rating_{t1} – superstructure rating_{t0}
	Change in the condition of the substructure of the bridge	Substructure rating_{t1} – substructure rating_{t0}
	Change in the condition of the slope/channel protection of the bridge	Slope/channel protection rating_{t1} – slope/channel protection rating_{t0}
	Air pollution	Emission amounts
	Water pollution	Emission amounts
	Noise pollution	Emission amounts

Component 2: Deciding on the Size of the DMU

DEA is a method to measure the relative efficiency of comparable units with an ultimate goal of improving their performance. Therefore, a homogenous set of units (DMUs) needs to be included in the analysis.

One other issue that needs to be considered during the selection of DMUs is determining the size of the data set. Such determination is accompanied by a trade-off. The larger the population of the data set, the larger the probability of capturing high-performance DMUs that would form the efficient frontier. Furthermore, as the number of DMUs in the data set increases, it is possible to incorporate more variables into the analysis (due to the reason discussed in Component 4 below). On the other hand, the larger the population of the data set, the larger the probability of risking nonhomogeneity within such data set (*19*).

Component 3: Addressing the Issue of Uncontrollable Factors

There are many external and uncontrollable factors (as shown in Table 1) that affect the road maintenance performance such as the environmental factors (e.g., climate, location) and operational factors (e.g., traffic, load). The developed framework needs to incorporate all factors to provide leveled comparison for different units trying to maintain roads facing different circumstances. This is mainly because disregarding such external and uncontrollable factors may lead to unfair comparisons in which the performance of a maintenance strategy may look better than another just because the former is being executed in a road portion that is easier to maintain due to its advantageous location as far as such external and uncontrollable factors are concerned.

As detailed in Ozbek (*18*), there are different approaches that can be used to address this issue. Depending on the specific case, a particular approach can be chosen to be used along with the appropriate DEA model to consider the effects of uncontrollable factors on the road maintenance efficiency.

Component 4: Refining the Comprehensive List of Variables

Running the DEA model using a large number of variables (as the ones shown in Table 1) would shift the compared DMUs towards the efficient frontier, resulting in a large number of DMUs to have high efficiency scores. The reason for this is as DEA allows flexibility in the choice of input-output variables' weights, the greater the number of variables included in the analysis, the lower the level of its discrimination. A DMU for which one particular ratio of an output to an input is the highest can allocate all of its weight to this ratio and become efficient. The total number of such ratios will be the product of the number of inputs and outputs. This product is a practical indicator of the minimum number of efficient units that will result from the implementation of DEA. Thus, in a case with four inputs and four outputs, DEA would result in at least 16 efficient DMUs. A suggested rule of thumb to achieve a reasonable level of discrimination is that the number of DMUs should be at least $2 \times m \times t$ where $m \times t$ is the product of the number of inputs and number of outputs (*20, 21*). Therefore, once the initial comprehensive list of variables is developed, such list needs to be reinvestigated and refined to be able to increase the discriminating power of the DEA models. Such refinement can be performed by means of a variety of approaches such as analytic hierarchy process, regression analysis, and principal component analysis (*18*).

Component 5: Preparation of the Data to Be Used in the DEA Models

As in any data-intensive modeling approach, the raw data gathered for the input–output variables as well as the uncontrollable factors need to undergo a substantial amount of data processing such as: (*a*) mining and cleaning to be able to obtain accurate records that can be used in the DEA model and (*b*) conversion into the format suitable to represent the variables to be used in the DEA model.

Component 6: DEA Model Selection

DEA models can be mainly grouped as (*a*) the model for processes experiencing constant returns to scale (CCR model) or the model for processes experiencing variable returns to scale (BCC model) and (*b*) input-oriented model or output-oriented model.

To select the right model, one needs to answer the following series of questions (*9, 16*):

1. Are DMUs within the data set experiencing constant returns to scale or variable returns to scale?
2. Are the decision makers more flexible and interested in changing (increasing or maximizing) the outputs of the DMUs or changing (reducing/minimizing) the inputs of the DMUs?

The answer of the first question will help deciding on whether to use the CCR model (*15*) or the BCC model (*22*). Once such decision is made, the answer of the second question will identify whether to use an input-oriented or output-oriented model.

Component 7: Running the DEA Model to Obtain the Results

This is the phase in which the model as identified in Component 6 is run by including the variables identified in Component 1 (as refined in Component 4) and DMUs identified in Component 2. Given the heavy computation requirements of the DEA models, usually this phase is performed with the help of appropriate software that is specifically designed to solve DEA problems.

Component 8: Deriving Overall Conclusions About the Results of the DEA Model

As discussed earlier, the framework presented herein is able to identify (*a*) the relative efficiency of different units in performing road maintenance services, (*b*) the benchmarks (peers) and targets that pertain to the inefficient units (in an effort to inform the decision-makers within such units of possible efficiency improvements than can be secured in the future), (*c*) the fundamental relationships between the maintenance LOS and the budget requirements, and (*d*) the effects of the environmental and operational factors on the road maintenance efficiency of units.

Even though DEA can identify inefficiencies, it does not directly pinpoint the underlying causes of inefficiencies of DMUs (*23*). Nonetheless, the results of DEA can be utilized to direct decision makers' attention to developing a better understanding of the reasons why some DMUs are located on the efficient frontier and are thus efficient and why others are inefficient. DEA may trigger decision makers to try to identify the differences in formal structures, operational practices (managerial practices, field practices, etc.), or other organizational factors of the DMUs that may account for the observed efficiency differences in these DMUs. The overall objective of DEA is to assign organizational meaning to the observed efficiency differences and to determine the organizational changes that the inefficient DMUs will need to undertake and how to implement such changes. The common methods used to reach such objective are benchmarking and describing and documenting the best practice processes of the DMUs that are efficient (i.e., located on the efficient frontier) (*16*).

CONCLUSIONS

This paper introduced a comprehensive framework that has been developed to measure the overall efficiency of road maintenance operations while considering the effects of external and uncontrollable factors (climate, traffic, etc.) on such overall efficiency. Such framework heavily relies on a modeling approach named DEA. DEA was utilized to develop the efficiency measurement framework mainly due to its ability to incorporate multiple inputs and outputs and accommodate external and uncontrollable factors, both phenomena common to road maintenance process.

The framework developed by this research, by pointing out the efficiency improvements that can be obtained and by identifying the peers to work with to realize such efficiency improvements, becomes a possible tool that can be utilized by state DOTs that are searching for ways to achieve better road maintenance efficiency.

It is important to note that the developed framework was successfully implemented to identify the relative road maintenance efficiencies of 8 counties of Virginia under the jurisdiction of the Virginia DOT (VDOT). Such implementation covered 215 mi of Interstate that fall within the limits of the following counties in Virginia: Albemarle, Alleghany, Augusta, Fauquier, Henrico, Roanoke, Rockbridge, and Spotsylvania.

The findings of the research outlined herein contributes new knowledge to the maintenance management field in the road infrastructure domain by providing a framework that is able to differentiate effective and efficient maintenance strategies from effective and inefficient ones; as such, the impact of such framework is broad, significant, and relevant to the decision-making process performed by the maintenance managers

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Maintenance Quality Assurance in North America
State of the Practice

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Constrained resources are increasingly impacting how many state transportation agencies evaluate and fund their transportation projects and priorities. Many states are looking for accounting tools and modified business practices to analyze transportation maintenance expenditures and justify ongoing maintenance budgets. There is an increasing demand on the part of the traveling public and within agency leadership for accountability and better understanding of the returns on maintenance investments. One approach to meeting these demands is to combine sound maintenance management principles with outcome-based maintenance performance measures through transportation maintenance quality assurance (MQA). The idea of quality in maintenance was first considered in the 1960s as a part of a maintenance management system concept. The notion of quality in highway maintenance has gained momentum in recent years as the national focus shifts from infrastructure design and construction to maintenance and rehabilitation. There is a general lack of understanding between the cost of MQA programs and the outcomes associated with those costs. States need specific examples of how funds put into an MQA program payoff. This presentation will draw from the proceedings and findings of the fall 2008 national peer exchange on the subject and the results of an ongoing synthesis of state programs. The presentation will provide an up-to-date assessment and analysis of what and where MQA is, how programs are evolving, and what needs to occur to make MQA an established business activity in state agencies. On September 23–24, 2008, more than 50 transportation professionals from around North America gathered in Raleigh, North Carolina, for the second national peer exchange on highway MQA. The purpose of the peer exchange was to give an overview of MQA evolution, foster a professional network for sharing relevant information, provide a forum for comparing programs, and determine how MQA could be better integrated into overall asset management programs. Through break-out sessions, states will address best practices, targets and thresholds for winter operations, pavement, roadsides, and traffic signs and markings. The gathered professionals will also explore reaching a common definition of MQA programs nationally and discuss use of common measures. The companion synthesis effort closely looked at MQA programs being used today on a state-by-state basis and compared the evolution of those programs since a similar analysis in 2004. The 2008 update also provided guidance and insight into how maintenance quality has changed over the past 4years as states are developing more mature systems and dealing with budgetary issues. The proposed presentation will include state case studies to demonstrate and identify correlations between funding and maintenance.

Performance-Based Contracting and Asset Management

North Carolina Department of Transportation's Performance-Based Contracting Experience in Charlotte

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In 2005, the North Carolina General Assembly passed legislation stating "the Department of Transportation may implement up to two performance-based contracts for routine maintenance and operations, exclusive of resurfacing." This legislation began North Carolina Department of Transportaion's (NCDOT's) entrance into performance-based contracting with its pilot project in Charlotte. This project includes about 700 lane miles of Interstates 85, 485, 77, and 277. As NCDOT began to prepare a contract document, identifying the scope of the project became a major undertaking. Much was learned from states that had gone before North Carolina in this endeavor and armed with Virginia and Texas experiences and NCDOT's own internal performance measures initiative a comprehensive contract document was prepared and advertised in June 2006. In March 2007, a performance-based contract was awarded to Infrastructure Corporation of America (ICA) and as with any new project both NCDOT and ICA had start-up challenges to overcome. Some of those included training DOT subcontractors and even ICA's staff in a new method of contracting and performance measures, locating facilities, and working through various communication challenges. In order to verify the contractor's performance, performance targets and semi-annual condition assessments are performed. The contractor's payment is based on how closely he adheres to these targets. This paper outlines the process and issues involved in the development and administration of North Carolina's performance-based contract including project selection, development of performance measures, lessons learned, and assessment methodologies.

North Carolina Department of Transportation (NCDOT) maintains the second largest highway system in the country with approximately 79,000 mi of roadway. This immense network of statewide, regional, and subregional roads covers every classification from Interstates to local collectors in every county. Needless to say, a system this extensive requires a large amount of maintenance resources and NCDOT's 9,000 field employees can not perform it all themselves. North Carolina has long contracted a portion of its maintenance operations using traditional line item-based contracts. Whether mowing by the shoulder mile or guardrail repair by the linear foot, NCDOT has had much success with these traditional contracts. This contracting mechanism served NCDOT well when inspection staff could be assigned to each contract to measure the items of work and direct the contractor's operations; however, as with all agencies, restrictions on hiring labor internally and an increased need for maintenance work to be performed has led to the need to try different types of contracts.

In 2005, recognizing NCDOT's need to try a new approach to contracting, the North Carolina General Assembly passed legislation stating "the Department of Transportation may implement up to two performance-based contracts for routine maintenance and operations, exclusive of resurfacing." NCDOT viewed this legislation as a chance to pilot performance-based contracting as a means to meet the growing needs of its highways and immediately began to assemble a team tasked with creating a contract document.

CONTRACT DEVELOPMENT

As NCDOT embarked on this endeavor, identifying the general scope of the project became a major undertaking. A contract development team reviewed documents from other states and engaged in a peer exchanges with Virginia Department of Transportation (VDOT) and Texas Department of Transportation (TxDOT) to learn from their experiences with this contracting method. Virginia had solely embarked on total asset management contracts in which they turned over all assets to the contractor in a defined corridor while Texas had experimented with narrower scope contracts such as rest areas or roadside items. The input gathered from both agencies along with an internal effort to develop performance measures led to a comprehensive contract document that was advertised in June 2006.

Under the leadership of the department's chief engineer, a team of in-house experts was assembled to more thoroughly investigate the scope and location of this first pilot project. This group consisted of experts in maintenance operations, North Carolina contract law, and contract administration. They began to identify the main factors which would influence the location and scope of this project. The major considerations were the regional availability of state personnel resources, traditional unit price contracting availability, the number of miles maintained in a given area, heavy traffic volumes, and the public demand for increased service.

Once all of these factors were identified, the corridor selection for this contract was narrowed to the three major metropolitan areas of North Carolina. Charlotte, North Carolina's largest city, was selected and has long been an area where contract resources were plentiful, recruitment of maintenance personnel difficult, the lane miles which required maintenance are growing rapidly as is traffic demand, and the public is increasingly demanding a higher level of service. With such a high-profile corridor, proceeding with a large fence to fence or performance-based contract seemed most appropriate. Some of the factors that weighed in this decision included the fact that most of the corridor was already maintained by multiple small contracts so letting one all-inclusive contract would be more effective. Turning over all assets within the section to the contractor would provide more clarity in roles of responsibility and would allow NCDOT personnel to focus their attention on other routes thereby improving the level of service there.

With the type of contract and the corridor selected, NCDOT reached out to the contracting community to get input into what size and duration of project would be most successful. Industry partners indicated that a project of at least 100 road miles with a longer duration would maximize resources and reduce overhead expenses. With this information, NCDOT identified the more than 700 lane miles of I-85, I-485, I-77, and I-277 in and around Charlotte. As shown in Figure 1, the project consisted of I-85 from the South Carolina line to Cabarrus County, all opened portions of I-485 around Charlotte, I-77 from the South Carolina line to Iredell County, and all portions of I-277 around downtown Charlotte.

As NCDOT began to prepare a contract document, it sought to learn from others who had experience with these contracts and established a dialogue with VDOT. VDOT agreed to partner

FIGURE 1 Routes identified as part of the performance-based contract.

with NCDOT allowing the agency to learn from their 10 years of experience with this contracting method. Through peer exchanges with VDOT that included document reviews, conference calls, and personal visits from VDOT staff to discuss their lessons learned NCDOT gained much insight into performance-based contracting.

Simultaneously, and unrelated to the project, NCDOT Operations began a major effort to fine tune it's already existing performance measures for its own internal maintenance operations. These new performance measures, combined with VDOT's contract documents were molded into a comprehensive contract document. Table 1 shows the 37 contract elements on which the contractor's performance is rated. Each of these elements has several specific performance standards which were detailed in the contract document.

While North Carolina was fortunate to have the basic pieces of a contract to start with, the development of a final document took several months and much iteration. Once the project corridor was established, the contract development team was expanded to include employees from the Charlotte area. This addition was extremely beneficial in providing a local perspective to the project as well as gaining buy in from the employees currently maintaining the routes and who would be tasked with administering the contract. The development team met several times to critique the draft contract and made repeated changes to the performance targets always with the goal of making them achievable at a reasonable cost. Through an iterative process of contract development, two question-and-answer sessions with the perspective bidders were held. The comments provided by the vendor community provided much insight into the pitfalls of the document and helped make North Carolina's contract even better.

North Carolina legislation allowed NCDOT to use a best-value procurement process without specifying the process. NCDOT chose to use its existing procurement process for design–build contracts to simplify things. This process included an initial request for qualifications (RFQ) phase in which the prospective bidders were narrowed to a short list bidders who were deemed qualified. During the initial RFQ phase, seven firms submitted their qualification packages and four firms were shortlisted. The shortlisted firms were Balfour Beatty,

TABLE 1 Contract Elements

	Element	Element
Bridges	Bridge decks	Pipes and culverts
	Superstructure	Retaining walls
	Substructure	Channel and slope protection
Pavement repair	Asphalt pavement repair	Concrete pavement repair
	Paved shoulder condition	
Shoulder and ditch	Low shoulder	High shoulder
	Lateral ditches	
Drainage	Crossline pipe (blocked)	Crossline pipe (damaged)
	Curb and cutter (blocked)	Curb and gutter (damaged)
	Drop inlets, CBs, etc. (blocked)	Drop inlets, CBs, etc. (damaged)
Roadside appurtances	Guardrail–cablerail	Concrete median barrier
	Noise walls	Impact attenuators
Roadside	Mowing	Brush and tree control
	Turf condition	Litter and debris removal
	Uncontrolled growth	Landscape beds
	Slopes	
Traffic–Intelligent transportation systems (ITS)	Pavement markings	Pavement markers
	Ground-mounted signs	Overhead signs
	Roadway lighting	Words and symbols
	Sign lighting	Delineators

Blythe Construction, DeAngelo Brothers, Inc. (DBI), and Infrastructure Corporation of America (ICA). These qualified bidders were then provided with a draft contract document and invited to attend two question-and-answer meetings and produce an request for proposal (RFP) detailing their approach to the project. Each bidder was then given an opportunity to make a presentation about their company's capabilities and introduce to the review committee staff that would be on site during the project. The contract was eventually awarded to ICA on March 12, 2007.

CONTRACT AWARD AND START-UP

Once the contract was awarded, the project was made available to ICA on July 1, 2007. The contractor, as well as NCDOT, immediately began making preparations for the start.

Start-up challenges faced by NCDOT included identifying the project administration staff and preparing them to manage this very different type of contract. Armed with advice from VDOT, job descriptions were created and positions identified to function as project manager and project inspectors. Having no idea how much staff would be needed to handle the 131-centerline-mile project, NCDOT elected to start with a small staff of three full-time employees and bring in others as needed. These employees were brought in to all project meetings and trained on the differences between traditional and performance-based contracts. VDOT again offered to have these individuals come to Virginia and spend time with their contract staff on existing projects. Two of these training trips were made to Virginia by NCDOT staff; one by division managers to talk with their VDOT counterparts about the start-up and assessment process and one by project administration staff to review day-to-day project operations.

Other NCDOT preparations included locating staff office space, training employees, developing detailed assessment methodologies, determining and acquiring hardware and software needs to administrator the contract, and setting up a partnering workshop with ICA. Additionally, procedures had to be developed on how to track and monitor contractor's daily performance, such as timeliness measures, and how to communicate this information to the contractor. Several meetings were held in Charlotte with central maintenance staff, division managers, and the project team to discuss expectations and challenges.

ICA also had start-up challenges in locating their operations facility, defining their project team, and educating local subcontractors on the performance-based contracting method of work. ICA expected its subcontractors to also sign performance-based subcontracts and many contractors did not completely understand the concept. The resistance from subcontractors required ICA to expend some effort on education to finally get contracts with their subs.

On May 8, 2007, a partnering workshop was held between ICA and NCDOT with FHWA facilitating. This session established a working relationship and set out common goals for the project. As this was the first project of this type in North Carolina, everyone was very interested in seeing it be successful and using FHWA as the facilitator set the tone for their involvement in the projects success. Some of the outcomes of this workshop included a project charter which developed a mindset of cooperation between all parties and a dispute resolution process which gave everyone a roadmap of how to escalate any issue where agreements could not be made at the project level.

As with all new contracts, growing pains occurred during the first year of the contract and these were compounded by the fact that this was a new type of contract for NCDOT. A major contracting issue faced during the first year was all project personnel becoming familiar with performance-based contracting as opposed to traditional line item contracts where the NCDOT staff direct the contractor's operations. This brought challenge to NCDOT staff that would see needs and want to direct the contractor go and make repairs. It was also challenging to ICA staff and subcontractors to not ask for direction from the NCDOT project staff. This was particularly challenging when subcontractors moved from traditionally reactive NCDOT maintenance contracts which provided much direction to this contract where the expectations of the contractor were more proactive with a lower degree of NCDOT direction. These situations defeated the purpose of performance-based contracting where the contractor is encouraged to plan and work as he sees fit to meet the performance targets allowing him to maximize his resources and be innovative.

CONDITION ASSESSMENTS

During the development phase of the contract, NCDOT decided to rate the contractor's performance at 6-month intervals. Defining an assessment methodology was a challenging process. NCDOT had an existing condition assessment methodology for its own internal use and after much investigation NCDOT chose to modify its own assessment methodology. NCDOT's contract assessment process samples 0.2-mi roadway sections for linear features as well as pulling random samples from inventories of point features such as pipes and bridges. Once these sections are identified, assessment teams are brought in to complete the rating and record their findings in a data collector device.

The decision was made to keep the day-to-day project personnel segregated from the assessment process to protect their daily objectivity. Instead, NCDOT pulls in assessors from other local division resources. All assessments are managed by central maintenance staff, again trying to protect the objectivity of the local division personnel. Central staff pulls the random samples, trains the assessors, answers questions, and conducts spot checks during the rating period and finally compiles the results and distributes the scores.

To get a realistic idea of the condition of the identified roadways prior to award, an initial assessment was completed by NCDOT and this data was given to all potential bidders. This assessment was done in part to give the bidders a general idea of the condition but also to allow NCDOT to evaluate the targets set in the contract. By analyzing the initial assessment data and the performance targets it became clear that the contractor would not be able to meet the contract requirements in the first 6 months of the project. A decision was made to lower some initial targets and raise them incrementally during the first 2 years of the contract. This allowed the contractor to steadily work at increasing some of the lower scores without having to expend a massive amount of effort on the front of the project thereby lowering the bid price. Table 2 shows how each element's performance targets increase during the first 2 years of the contract.

This contract included a partial payment based on performance clause in which the contractor's payment is based on how successfully he meets established targets. Another way NCDOT attempted to help the contractor meet the performance targets was to waive the pay for performance provision for the first 6-month assessment. This meant that the contract payment for the first year would not be affected by any assessment. This decision achieved two outcomes. First, it took the pressure off the contractor giving him 1 year to achieve the initial targets and it gave both NCDOT and ICA a chance to get oriented to the North Carolina assessment process and work out any discrepancies that arose.

While the contractor's payment was not affected during the first year, all subsequent monthly payments were subject to the performance fee structure outlined in the contract and payments can be reduced in the future for failure to meet the targets. To date, there have been two completed assessments and one assessment is currently underway. As shown in Figure 2, the overall condition of the project has increased from 77 when the contractor took over the project to 85 at the spring assessment.

In June of this year, the department completed its second assessment of the project and while results were improved, the contractor's performance was still below the established targets on several items. In this second assessment, the contractor met the performance targets on 73% of the contract elements and failed to meet the targets on 27% of the elements. Figure 3 shows a sampling of the scores and targets for the traffic elements category in the June assessment. In this category, the items failing to meet the performance targets were pavement markings, pavement markers, roadway lighting, and sign lighting. This contract covers some very old sections of I-85 and I-77 and determining the reason for lighting failures was difficult. After a joint investigation into the roadway and sign lighting elements, NCDOT and ICA came to the conclusion that enough ambiguity existed as to the reason for the failures of these items that the contractor was not held responsible. The contract specifically states that the contractor is only responsible for the lighting fixtures from the ground up and many of these lights are not functioning because of the underground wiring.

TABLE 2 Element Performance Targets

	Element	2007 Target	2008 Target	2009 Target
Bridges	Bridge decks	80	85	90
	Superstructure	80	85	90
	Substructure	80	85	90
	Pipes and culverts	90	90	90
	Retaining walls	90	90	90
	Channel and slope protection	90	90	90
Pavement	Asphalt pavement repair	95	95	95
	Concrete pavement repair	95	95	95
	Pavement shoulder condition	90	90	90
Shoulder and ditch	Low shoulder	85	90	95
	High shoulder	85	90	95
	Lateral ditches	85	90	95
Drainage	Crossline pipe (blocked)	85	90	95
	Crossline pipe (damaged)	85	90	95
	Curb and gutter (blocked)	85	90	95
	Curb and gutter (damaged)	85	90	95
	Drop inlets, CBs, etc. (blocked)	85	90	98
	Drop inlets, CBs, etc. (damaged)	85	90	98
Roadside appurtances	Guardrail–cablerail	95	95	95
	Concrete median barrier	95	95	95
	Noise walls	95	95	95
	Impact attenuators	95	95	95
Roadside	Mowing	90	90	90
	Brush and tree control	85	90	90
	Turf condition	80	85	90
	Uncontrolled growth	70	70	70
	Litter and debris control	95	90	95
	Landscape beds	70	80	80
	Slope	95	95	95
Traffic–ITS	Pavement markings	85	90	95
	Pavement markers	85	90	95
	Ground signs	92	92	92
	Overhead signs	92	92	92
	Roadway lighting	90	90	90
	Words % Symbols	85	90	95
	Sign Lighting	90	90	90
	Delineators	90	90	90

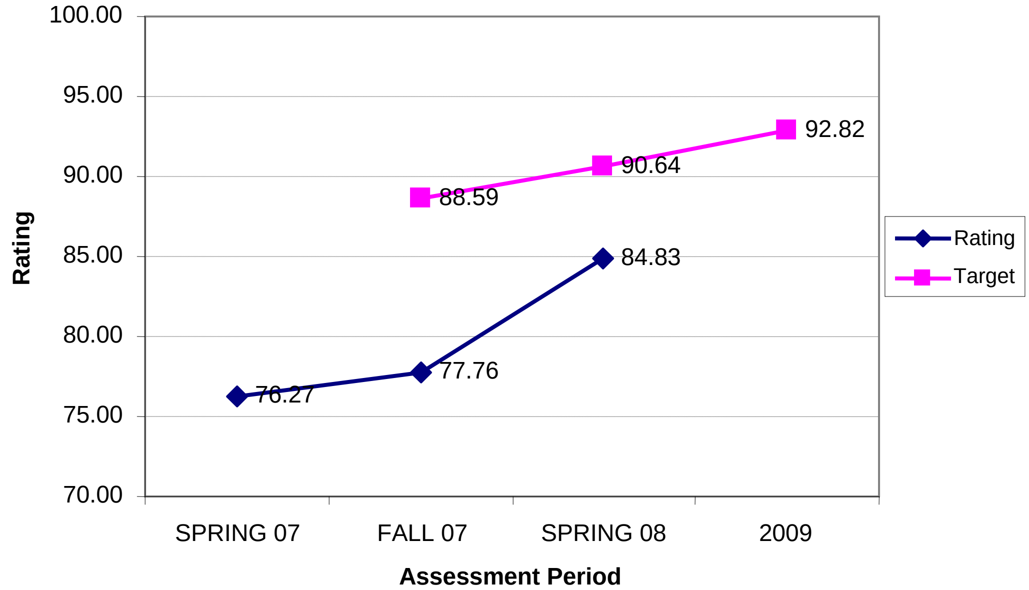

FIGURE 2 Overall project assessment scores and targets.

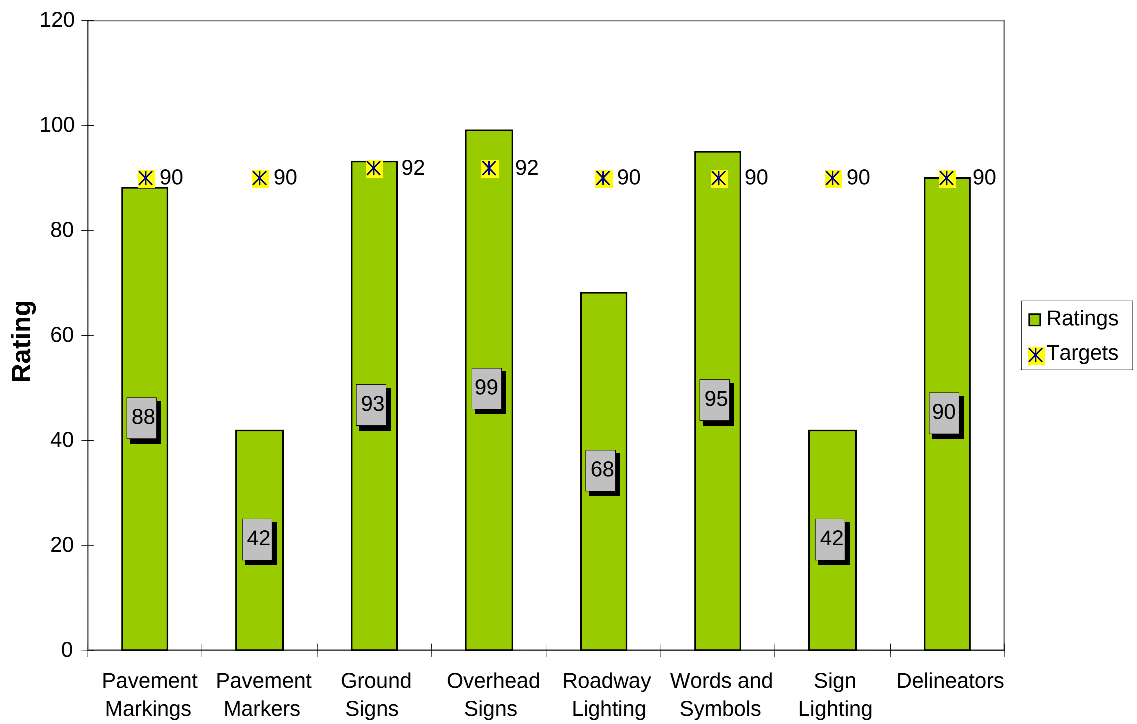

FIGURE 3 Traffic elements assessment scores.

To ensure that the assessment scores are valid, the numbers of samples needed to ensure statistical accuracy have varied in each assessment. The department is utilizing the statistical sampling methodology developed by Jesus M. de la Garza for VDOT's performance-based contracts to determine the appropriate sample sizes needed for each assessment. This methodology requires that the sample size needed be dictated by the confidence level required and the condition of the asset as determined in the previous assessment; high ratings yield small sample sizes and low ratings yield larger sample sizes. This fluctuation in the number of samples required has affected the duration of completion of the assessments. These assessments have taken an average of 25 working days with 10 two-person teams to complete them, However, improvements in the technology used to assess the items has led to great reductions in work effort and time involved.

For the initial assessment completed prior to contract award, paper forms were completed and then hand entered into a database. Recreational-grade Global Positioning System (GPS) devices were used to locate inventory items. Subsequent assessments were conducted with handheld PDA-type devices with recreational grade GPS receivers which led to difficulty finding the sample sections and inventory items. The assessment currently underway is being conducted using tablet PCs, ArcPad Data Collection software, and Bluetooth recreational-grade GPS receivers. This change in technology appears to be significantly reducing data collection time by allowing the user to more quickly locate and assess the identified 0.2-mi sample sections and inventory items required for the assessment.

It is too early to determine the overall impact of the deployment of this new technology, but it appears that the assessment time has been reduced from 25 working days to 15 working days and from 10 teams to eight teams. It is anticipated that this will further reduce the number of teams in the future to no more than six teams and have the assessment completed within 20 working days.

ISSUES AND CHALLENGES

Throughout the development, advertising, awarding and administration of North Carolina's first performance-based contract there have been issues to overcome. From the very beginning, NCDOT knew this would be a very challenging, but also a highly rewarding contract and it has not disappointed. Various issues have loomed large at different times in the contract process making this one of North Carolina's most challenging ventures.

During the contract development phase, defining the scope and performance targets of the contract became critical components. The entire success or failure of the contract would be determined by these components. NCDOT, wanting to have a successful and challenging contract, believed the location of Charlotte was a good choice. NCDOT was fortunate to have existing performance measures for its own staff and having the access to VDOT and TxDOT data was invaluable. This data gave realistic comparisons to existing contracts and NCDOT was better able to create reasonable performance measures.

Other challenges during the development phase included obtaining buy in from internal NCDOT staff. NCDOT employees were apprehensive and had to be assured that their jobs would not be lost.

Challenges during the contract advertising and award phase included conducting the initial assessment to give the contractor an idea of condition. It was only after NCDOT was underway with the RFP process that everyone realized how critical determining this initial condition became. This resulted in a delay of the letting date but provided the opportunity to resolve a number of assessment issues. Also, contractor question and answer sessions were also crucial to gathering input from industry on the hidden pitfalls in the draft contract document. An additional challenge was preparing the engineer's estimate, specifically, adjusting for increased level of service, overhead, profit, and risk.

The responsibility of snow and ice response was one challenge that was faced throughout all phases of the project development. Early on, NCDOT struggled with whether to release snow and ice control to the contractor. North Carolina, and particularly Charlotte, does not have many days in a year where snow and ice are problems and there was a concern over the cost to provide this service. Contractors would have all the same supply and environmental issues NCDOT already had and NCDOT was not going to get out of the business of snow and ice control because of its other roadways. In the end, NCDOT chose to bid snow and ice control as an alternate to get an idea of the price. Once bids were in, NCDOT chose not to pursue the snow and ice option due to cost opting to continue to perform this work in house. All the contractors' bids for snow and ice were at least 20 times what NCDOT spends in an average winter on snow and ice control. Issues surrounding the contractor's price were availability and placement of material stockpiles, availability of subcontractors to perform the work within the time requirements of the contract, and the cost of just being immediately ready. NCDOT believed the price put on this level of preparedness was not cost effective.

During the contract start up phase, challenges included identifying project staff and familiarizing everyone with the performance-based contract process. This complete reverse of mindset did not happen overnight and took much effort on the part of NCDOT and ICA staff.

And finally during the contract assessment phase, issues have arisen about the reasonability of performance targets. When NCDOT set some of its performance targets, it understood that they were high goals to achieve. In the contractor question and answer sessions these targets were always discussed and contractors were asked how they would pursue obtaining these goals. Now over a year into the contract performance targets have proven to be an issue. Recently, given the effort shown by the contractor and the appearance of the project, NCDOT has begun to reevaluate some performance targets. ICA and NCDOT staff have met on site to evaluate some targets in the field and continue to discuss the targets; however, no agreements have been made.

All of these issues have been faced head on in cooperation with the contracting industry, specifically ICA, and that approach has led to a contract that North Carolina and the industry can be proud of.

LESSONS LEARNED

NCDOT has learned many valuable lessons along the way. Without the support of other state highway agencies and the contracting industry that was already using this contracting method many hours would have been spent needlessly on inventing what already existed. The major lessons learned that would benefit any agency beginning the pursuit of a performance-based contract include the following.

Find a Mentor

Develop a partnership with one or more states that have pursued these contracts and obtain copies of their contract documents. Meet with them on a regular basis as you develop your contract and discuss issues that have come up.

Develop a Detailed Scope Early in the Process

Decide what you want your contract to include and not include early in the process. Always refer back to this scope as things come up and questions arise about adding to the project.

Be Reasonable with Deadlines

Developing a contract of this type takes time. Be realistic with how long it will take to move through the phases. Give ample time to thoroughly read and digest the contract. Shortening the time line will only lead to errors and contract negotiations later.

Listen to the Contracting Community

Be open to the contracting community's advice. They have vast experience in these contracts and various states' perspectives. Don't be too proud to hear them out. They may have solutions that have worked on other contracts that you never thought about. Hold question-and-answer sessions.

Use Technology

Technology can be a tremendous help. Take the time to ensure the right technology is employed from the start. Most of the technology needed for data collection purposes is readily available off the shelf and can be easily customized for your agency's needs.

Recreational-grade GPS equipment is inexpensive and easy to acquire and use, however the coordinate information it provides is not accurate enough for all inventory purposes. However, recreational-grade GPS, when utilized in conjunction with relatively current aerial photography and the appropriate software for assessment purposes, communicates relative location information to the user very effectively and helps to overcome the significant error that can accrue with recreational-grade GPS devices. Mapping-grade GPS devices should be utilized for initial inventory purposes.

Put a great deal of thought into your database up front. Make sure you create a format that allows room for as much expansion and modification in the future as possible.

There Is No Such Thing as Too Much Detail

The more detail provided up front in a contract the less questions that come up later. Fully define what is expected of the contractor and what specific requirements he must meet. For example, if there are special environmental requirements or traffic control issues include them in the contract.

Conduct an Initial Assessment and Take Pictures

Develop a detailed inventory and know the condition of the project's elements before award and share this info with the bidders. While the contractor is responsible for gathering this data himself, giving him your data will only make the project better. Taking pictures of inventory items also helps you remember what things looked like prior to contract award.

Be Open with Your Agency Employees

These types of contracts make employees question their job security like no others. Keep open lines of communications with all employees providing updates on the status of the project and reassuring them of job stability. Be sure to include the local employees who will be most affected by the contract in all contract discussions as early as possible. This develops buy in and overcomes issues of bias and conflict later on.

Be Reasonable About the Size and Scope of the Project

Contractors also have overhead expenses that must be factored into their bids and the more these costs can be distributed through a project the better the pricing. Projects of around 100 mi in total length tend to be good break points. Smaller projects are not cost effective for the contractor while larger projects may be difficult to manage.

Performance-Based Contracting—Yes or No
An In-Depth Analysis

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In the fall of 2006 the Indiana Department of Transportation (INDOT), initiated a study to investigate performance-based contracting of maintenance operations. One of the main impetus for the study is that INDOT started a 10-year road building program called Major Moves that will add more than 1,000 lane miles to the current network. With this addition and coupled with a trend of reduction in maintenance personnel, INDOT is planning how maintenance will be performed. One option is the use of performance-based contracting (PBC). This study evaluated many aspects of PBC and produced an in-depth analysis of PBC. Information on how to implement, pros and cons, and recommendations to consider are described in this paper. Other options are discussed in the paper. This information should be helpful to agencies contemplating PBC for maintenance operations.

A question that has been raised during the last few decades is why outsource road assets, activities, or services? It has been agreed that without tentative attention, roadway conditions will continue to worsen. Government agencies are faced with uncertain fiscal results and public contestation; hence, government needs to "do more with less" (Zietlow, 2005). Outsourcing through public–private partnerships (PPPs) offers a solution to improve quality and save money. The goals that government agencies typically seek to achieve by outsourcing road segments are as follows (Segal et al., 2003):

- Reduce costs. Achieving cost savings is one of the most important reasons for outsourcing road and highway construction and maintenance operations. However, cost savings is not the only issue; level of service (LOS), quality of the constructed, maintained, and operated assets, and human resources are often disregarded. Hence, cost savings should not be considered as the only factor in determining whether to outsource or not.
- Increase efficiency. Literature has shown that a competitive system is more efficient and effective than traditional single-provider systems. In order to obtain the maximum possible value for money, some government agencies have outsourced their projects as part of efforts to improve overall system efficiency through competition and specialization. Outsourcing introduces competition, resulting in improvement of the government agencies' services. Since government services are threatened by a probable privatization, they need to become more efficient and finally provide better services to compete with the private sector.
- Improve quality. In order to be more competitive, private agencies need to produce high-quality work and ensure high performance. One of the most important factors for the awarding of contracts is past performance; hence, delivering low-quality service could reduce the likelihood that a private agency is awarded future contracts.

- Motivate innovation. Outsourcing through PPPs can produce innovative solutions. Since the overall goal to private agencies is profit, they try to achieve it by applying new methods in all levels; this way, they become both more competitive and capable of producing higher-quality services.
- Access expertise. Competitive private agencies typically have worked on various projects. As such, their experience is very significant. Government agencies that employ such expertise can gain access to new or specialized expertise that is not available in house.
- Precipitate project delivery. Government agencies do not have the required work force to maintain the existing infrastructure. On the other hand, the private sector is flexible on shifting human resources in order to meet time constraints.
- Increase flexibility. Outsourcing to increase flexibility is related to meeting peak demand. Agencies can use contractors when needed, an option that is not feasible in the case of the agency employees.

At the current time, there is considerable global experience with the practice of performance-based contracts (PBCs). This experience is accompanied by contestation on the true outcomes produced by PBCs with regard to qualitative (offered LOS) and quantitative (cost savings) results. Collected cost data indicates that PBC is not effective in saving agency money as reported in previous reports. Overall trends, advantages, and disadvantages are reported herein.

While U.S. agencies and other foreign road administrations are increasingly implementing performance-based contracting, a number of challenges are also being identified. First, agencies tend to be concerned that they may lose valuable in-house expertise due to the reduction of their involvement in roadway maintenance, as a result of outsourcing. Another issue is the LOS required for the outsourced facilities (or activities) that are included in the PBC. There is also concern regarding the risk allocation from the road agency to the contractor, and the ways the latter can manage it. Finally, there is a need to evaluate whether and under what conditions PBCs will lead to overall assets' improvement, and if they are cost effective in the long term.

MAINTENANCE PLAN

Officials from several U.S. state departments of transportation (DOTs), international road agencies, and several major contractors were contacted to discuss, suggest, and comment on their experiences regarding outsourcing of roadway maintenance operations, including PBC.

Major conclusions from these discussions are summarized:

1. Do not incorporate snow removal activities in PBC.
2. Initially, launch a 2-year PBC where few activities are incorporated in minor highways or secondary roads.
3. Experienced agencies and contractors may move towards a long-term (20 years) comprehensive PBC.
4. "Best value" should be the selection bid criterion.
5. The performance measures for specifying the PBC's characteristics are the cost savings, LOS, and public–political acceptability.

6. Cost savings can only be realized from well-qualified contractors, strong competition, and long-term contracts.
7. The liability issue is an important concern in the United States.
8. Hybrid contracts are the "right" approach to increase competition (and for the agency to feel more comfortable); the hybrid approach utilizes agency forces as the foundation for maintenance services and the use of contractors to supplement.
9. "24/7" callout is manageable by the contractors (however, cleaning crash scenes in a timely fashion is difficult).
10. Outsourcing roadway assets located near the contractor's facilities would be beneficial for both parties.
11. Performance monitoring should be performed at a frequency and level to adequately determine contractor performance.
12. Requirements should be developed to assure contractor meets requirements throughout the life of the contract.
13. Clearly identify the contractor and agency responsibilities in the contract, and develop a risk management sharing system.

With falling gas tax revenue, maintenance budgets are being cut. At the same time more is being built to maintain. So what are an agency's options?

1. Increase resources: equipment and personnel. This is highly unlikely.
2. Increase maintenance subcontracts including snow and ice removal activities.
3. Implement a PBC program that includes winter operations.
4. Reduce the LOS across the network.

Items 1, 2, and 3 require additional funding. Item 4 lowers the quality of the end product, but saves money. How will this play out with an agency? The following lays out information for evaluating and selecting these options.

Option: Increase Resources

Indiana Major Moves projects will add approximately 1,341 lane miles to Indiana Department of Transportation's (INDOT's) current network. Other capacity will be added through the normal work program. These additional requirements if maintained with state forces will require additional equipment, material, and people. INDOT analysis says that 40 new trucks will be needed to man the additional snow routes. From average lane mile cost data the additional annual maintenance expenditure will be close to $6,000,000. From a cost basis, this is the best option, but from a political perspective maybe the least preferred option because it grows government numbers.

Option: Increase Subcontracts

INDOT currently has a well-developed maintenance subcontract program. Activities such as mowing, guardrail repair, cable barrier repair, and other activities are done through subcontracts. With this experience and capability INDOT can easily expand this option and this would require the following:

- More contract managers will have to be developed.
- Inspection criteria may need to be refined or developed for new activities.
- An evaluation of the subcontracting industry by state region. This evaluation involves looking at activities and the availability of qualified and adequate number of subs for competition reasons. This evaluation will take time and should be performed by each district.
- Develop a training program for contract managers and inspectors to insure a uniform and well-structured program.

Option: PBC Program

Typically these programs are driven by political reasons and not business ones. PBC will allow INDOT to shrink its workforce and equipment needs. PBC will utilize private contractor resources to supplement public resources, a form of "redistribution" of resources. Other facets such as innovation are advantageous and documented herein. Plusses and minuses of this option have been well documented by other studies. Lessons learned from evaluating the PBC approach include:

- Most PBC programs are initiated for political reasons and not business reasons.
- PBC contracts are generally not cost effective for geographic contracts.
- PBC contracts that are facility specific (e.g., rest areas, bridge maintenance) have proven to be cost effective.
- PBC contracts create an environment for innovative solutions.
- PBC contracts have not handled snow and ice events well. Costs are for extreme weather events over a long time period for risk reasons. Most contractors are not equipped for extreme events while agencies can pull resources from less affected areas.
- PBC requires an agency to create a new organization, develop LOS criteria, perform baseline assessments, develop an assessment program, and produce a training program.
- Determine state contracting community's interest in performing maintenance activities.
- Snow and ice subcontracts are a viable option.

Option: Lower LOS

This is certainly not a desirable option but one that most agencies are trying to identify. As maintenance budgets are cut this will be reflected in lower LOS for most activities including snow and ice removal activities in the snow belt states. The impact on LOS requires an agency to evaluate expenditures for each activity and LOS standards and evaluate the impact on LOS with budget reductions. Certainly the robbing Peter to pay Paul principle will occur with this approach. For example, salt costs have increased significantly since the 2007–2008 winter. And next year's costs could double over this year. So will an agency order less salt and incur the risk of running out? They most likely will not for safety and commerce reasons. So to cover this increase, other activities LOS will have to be cut. To determine the ramifications from this action an agency needs to have well defined LOS criteria and corresponding activity costs.

The next section describes the essentials components and requirements for establishing a PBC program.

PBC PROGRAM COMPONENTS

A PBC program consists of an organization and two major phases, developing contracts and contract administration. This section describes this organization and what should occur in the different phases of the program.

PBC Team

A PBC program requires a new organization within an agency. This organization will be responsible for staffing, developing contracts, overseeing contracts, performing assessments, and determining contractor conformance and compliance to contract requirements. This organization must be put into place before contract development and selection occurs. What does this organization look like?

Initially a PBC program will run from the central office even though an agency may be decentralized like INDOT. An individual in maintenance will be in charge of developing the program. Initially this individual will spend a majority of his time in developing a contract. After that phase is completed, less of his time will be required to administer the contract.

For explanation purposes this individual will be called the PBC Administrator. To describe this individual and the PBC organization, the below tables (Tables 1 and 2) contain a job description and time requirement estimates for each program phase.

Contract development activities can be performed in parallel. This phase will take approximately 18 months to develop the initial contract. This phase may involve up to 10 employees and will require a full time administrator.

The administration phase is the execution of the contract and Table 2 describes the administrator duties.

This phase will not require a full time administrator. That individual will be available for other maintenance duties. This phase does require a fulltime contract administration team, consisting of a supervisor and inspectors. North Carolina DOT (NCDOT) had three full-time employees in their contract, FDOT uses two employees per contract, and VDOT has three employees involved in each transportation asset management contract.

LOS Program

An important component of a PBC program is establishing appropriate LOS criteria. This criteria is needed for establishing contract LOS requirements, developing a cost estimate, and for performing assessment evaluations of the contractor performance. These criteria must be clearly understood by the agency, the assessment team, and the contractor. The individual items must be described in language that leaves little room for misinterpretation and dispute.

Agency and Contractor Comparison

One aspect of a PBC analysis is to compare agency and contractor. Table 3 is a comparison of the various factors. This comparison helps to identify the strengths and weaknesses of a PBC program as well as requirements.

A PBC program is comprised of many different activities and participants; these fall into two main phases: contracts and administration.

TABLE 1 PBC Administrator: Contract Development Phase Duties

Phase	Activities	Estimated Time Requirements
Contract Development	Project selection. Determine project location, project length, and activities to include.	1 month
	Baseline assessment.This requires a team of approximately two to three to perform a field inventory of asset condition.	2 months
	Engineers estimate.This is created from the baseline assessment. Also, LOS criteria will establish engineer's estimate. Engineers estimate is adjusted by LOS requirements.	1 month
	Develop and test performance standards. Do standards exist? Other state standards should be consulted for comparison or for developing particular standards. The same team that performed the baseline assessment will be involved in this activity.	6 months
	Legislative action. Develop bill for legislative approval for best value and best and final offer bids. This is the preferred contract form.	12 months
	Develop contract language. This requires putting together a team comprised of legal, contracts, contract field manager, contractor association members, and others. Use other agency contracts as a guide.	12 months
	Develop assessment program. Issues to be decided are: who will perform the assessments, how many teams needed, rating system used.	2 months
	Training program. Training programs need to be developed for assessment teams and contract inspectors.	2 months

TABLE 2 PBC Administrator: Administration Phase Duties

Administration	Develop field team and guidelines for inspecting and documenting. Establish a partnering arrangement with the contractor.	1 month
	Perform assessments and determine contract pay amounts.	At specified intervals.
	Administer annual training for assessment teams.	1 month

TABLE 3 Agency and Contractor Comparison

Factors	INDOT	Contractor
Cost	Lane mile costs are lower with DOT forces.	Liability and insurance costs are added expenses.
Cost control		Long-term contracts with fixed costs over a multiyear period control costs and helps plan budgets.
Innovation		More innovation due to fewer restrictions on private companies. More motivation to reduce costs through innovation.
Experience	Higher levels, more local knowledge.	National firms will bid and sub out up to 90% of work.
Manpower needs	Fixed, reduced through attrition.	Flexibility in responding to manpower needs.
Equipment resources	Fixed	Construction equipment; respond better to changing needs.
Snow and ice removal	Experience and resources; able to shift resources in emergency situations.	Higher costs due to planning for worst case scenario. Extreme event experience and resources are questionable.
Administration	Less administration required for PBC contracts.	
PBC contract development	Requires up to 18 months involving five to 10 INDOT employees.	
Best value versus low bid	Best value preferred but requires legislation.	
Baseline assessment program	Standards and baseline inspection program has to be developed.	
Inspection program	Requires inspection program development, administration, and training.	
Facilities	Fixed	Lease space. Typically do not own or lease a DOT facility.
Long-term impact	Loss of experience and facilities.	Less competition over time.

Contracts

Developing an initial PBC contract takes a considerable amount of time and effort. Contract development may take up to 18 months to develop an initial contract involving up to 10 individuals. Items to consider for inclusion in the contract are the following.

- Work items. May include from right of way (ROW) to ROW or variations. Be specific and descriptive.

- Performance standards. Try to eliminate any gray and make the requirements. There should be very little room for interpretation.
- Selection criteria: best value. Combination of cost and technical qualifications, 70% technical proposal and 30% cost proposal or some variation. Best and final offer used if bids exceed engineer's estimate. Do not release engineer's estimate.
- Bond requirements. Bonds should be viewed as costs for the DOT to take over the contract if the contractor defaults. Instead of requiring a bond for the total contract (total duration), only a portion of the contract (1 year or 6 months).
- Liability limitations. Usually limited to a percentage of annual contract cost. One example is contractor out of pocket expense for unrecoverable property damage is 20% of the annual contract cost. Expenses over that will be picked up by the agency. Shared liability helps to keep costs down.
- Contractor assumes third-party risk with no limits on claims. For example, a $1 million limit on third-party lawsuits. Contractors have insurance to cover these expenses and the premiums are included in the contract.
- Response times, performance requirements, and penalty clauses must be clearly defined to minimize misunderstandings.
- Change order provisions help give the contract flexibility when conditions change.
- Make it a living contract so that current specifications and standards apply.
- Define how assessments will be done, frequency, who will perform, etc. Also, payment penalties for lack of performance should be clearly explained. Contested assessments and allowable recourses should have a provision.

Risk analysis should be performed when developing a PBC contract. An important aspect of this analysis is risk-sharing allocation. A proper balance between agency and contractor is the right approach because it affects the contract cost and performance expectations. A risk analysis looks at both agency and contractor responsibilities and tries to minimize exposure by looking at strengths and weaknesses of each.

A contractor tries to minimize risk. As perceived risk increases this is reflected in increasing contractor cost. For those risks that are unpreventable by the contractor, often insurance is sought to cover these. So it is mutually beneficial to evaluate risk and include the results of this analysis in the contract. Table 4 lists some typical risk factors that need to be considered while developing the contract.

Administration

Contract administration is the activities performed during the execution of the project. This mainly consists of daily supervision requirements and the assessment program.

For a typical size project, approximately 130 road miles, usually three individuals are needed including the field manager, costing approximately $150,000 annually. A field office or one close to the contract is needed.

TABLE 4 Risk Factors

1.	Best value contract is preferred because it allows for a better evaluation of contractor capabilities and performance than using low bid to award.
2.	Contract renewal. Establish a contract provision that provides for renewal to the existing contractor based on performance.
3.	Bond amount and duration. This should be set for a time duration and amount that will provide the agency the means to recover from a contractor default.
4.	Unrecoverable property damage limits. Monetary limits for this type of damage could be a certain percentage of the annual contract amount and for a single incident.
5.	Emergency response requirements. Describe any response requirements or remove completely from the contract and let the agency handle these emergencies.
6.	Optional assessments. Allow the contractor recourse if there is disagreement in the assessment scores.
7.	Weather effects. Remove actions required to respond to weather events such as flood and tornados.
8.	Third-party lawsuit limits. Most state agencies have protection in this area. The contractor should be provided some form of protection as well.
9.	Response time requirements. Response times should be reasonable for contractors. For example, describe how much time is allowed for replacing downed signs.
10.	Cost escalation clauses. Allow for cost increases either set by a certain annual percentage or by cost indices.
11.	Assessment criteria. Contractor performance measures should be written that eliminates misinterpretation and removes misunderstanding.

- Partnering should be a part of any PBC contract.
- The assessment program is very important. Administrating will take time and resources. Objectivity, speed, accuracy, and safety are key ingredients. NCDOT is spending approximately $90,000 per assessment.

Annual training is important for assessors, inspectors and contract administrators. Training should happen before the contract starts and annually throughout the life of the contract.

Contractor Innovation

PBC contracts provide an environment that fosters contractor innovation. Contractors have the latitude to meet the performance standards and the time (multiyear contracts) to be innovative. A long-term contract allows for spending upfront money that pays off over the contract life through innovation. Some cited examples are:

- Different types of pavement treatments.
- Incident management.
- Roadway lighting.
- Contractors have more flexibility in negotiating subcontracts and developing subs over the contract period.

Outcomes

This section describes some outcomes experienced by agencies that have used PBC for a long time or just starting.

- The Virginia DOT (VDOT) program started in 1997 mandated by the state legislature. Its goal is to use PBC on all Interstates by 2009. To date no layoffs have occurred but reduction of approximately 2,000 employees through attrition. Currently there are approximately 5,700 employees in maintenance.
- The Florida DOT (FDOT) program started in 2000 and as a result maintenance forces have been reduced 25% through attrition. In 1994, FDOT performed 60% of maintenance work and contracted out 40%. In 2008, 20% of maintenance is performed in house, 40% through asset management, and 40% with traditional contracts. Some maintenance yards have closed and consolidated. FDOT has lost capabilities due to lack of experience.
- Some Canadian provinces have privatized all maintenance, so they have reached a point of no return.
- Typically, PBC contractors subcontract out most of their work, 75% to 80%. Subcontractors are usually local contractors.
- Contractor performance at end of contract period has been a problem due to lack of penalty. If assessment times are known then contractor performance will fluctuate. Minimum performance is a sore point. For example if LOS is 80, then filling eight of 10 potholes meets the standard.
- NCDOT completed the first year (July 2008) of their initial PBC contract. The contractor is not satisfying performance requirements, so the monthly pay of $482,976 is being reduced $90,000 until the next assessment, which is done every 6 months.
- Contracts have worked well in high-incident areas.
- Contracts have not worked well in emergency conditions.
- One agency is spending less on rest stops and security through PBC.

PBC is driven by performance standards which tend to focus contractors on the short term. This can have a negative effect on long-term asset condition.

Possible Sources of Savings

- Less management overhead due to consolidating subcontracts into one and less inspection required.
- In some cases a contractor can lower labor costs through improved productivity and lower labor rates.
- More efficient use of equipment.

SNOW CONTRACTS

In snow belt states, snow and ice removal activities account for a significant portion of the overall maintenance budget and equipment needs. Approximately 33% of INDOT’s maintenance budget is spent on snow and ice removal. For INDOT, new snow routes are being planned and additional resources will be needed. One option is to use subcontracts. Virginia includes snow and ice removal in their PBC contracts. North Carolina has developed subcontracts. Both these approaches are described.

VDOT says that snow and ice removal is the largest cost item since contractor plans on a 50-year extreme case occurring during the contract life. In one transportation asset management contract approximately 50% of the contract cost was for snow and ice removal. Also, it has been witnessed in Virginia and Oklahoma that contractors do well on average storms and not on larger winter events.

NCDOT uses two types of subcontracts.

- Contractor provides trucks equipped with spreader and plow. NCDOT provides material. Contractor is reimbursed on hourly basis.
- Contractor bids on outfitting truck and NCDOT sets the hourly rate. A 5-year contract is established, so the contractor is reimbursed 20% annually for the equipment. Brine distribution is included in the contract.

Call out requirements is included in both contracts.

The option of INDOT receiving more equipment and personnel in maintenance operations is unlikely. INDOT will need to develop a subcontracting program for snow and ice. This program should be tested over a couple of winter seasons before implementation. The program should evaluate how private companies can best supplement INDOT efforts under what weather conditions and on what road type.

INDIANA CONTRACTORS

One reason for utilizing contractors particularly for winter operations is they have equipment and personnel available during this time of the year. This is their slow season and these resources are usually idle. So why not utilize these resources for snow and ice removal.

Multiple meetings were held with Indiana contractors in which PBC contracts were explained and discussed. Out of these discussions came the following:

- Liability issues are a big concern. Protection from third-party lawsuits and indemnification is desired by the contractor.
- Most contractors have the resources to do all maintenance activities with a few exceptions. Those exception activities they can respond through subcontracts.
- Recommend starting the program with a short-term contract (2 years) to evaluate approach.
- Escalation clauses desired for materials and fuel.

LEGAL–POLITICAL ENVIRONMENT

Legal issues and risk have a significant impact on the PBC approach. Most states have indemnification protection from lawsuits. This protection usually limits damages to a certain amount. Contractors do not have this protection so this risk is covered through insurance and these premiums are in their costs. Contractors generally view these risks very conservatively by planning and charging for the worst case scenario. These hidden costs significantly influence PBC costs. The current legal environment or atmosphere in this country increases these risks.

Currently Indiana's political environment is swinging away from privatization. Audits and studies are revealing that some privatization programs are costing taxpayers more money than if the services were performed by a state agency. These findings can make it politically very difficult to get legislative approval for these contracts.

COST ANALYSIS

A good cost analysis requires all comparison factors to be equal or close to each other. This is very difficult when comparing PBC contracts with in-house costs. Factors such as varying LOS, activities included and excluded, the way agencies record and track costs, overhead costs, are factors that influence these cost comparisons.

Agency In-House Unit Costs

Cost data collected from the below agencies are compared on a lane mile cost basis. These calculations are not shown due to space limitations but are summarized below. An equal basis is important with any comparison and that was the goal with these numbers.

- INDOT: $4,500* per lane mile on Interstates; includes snow and ice control (* estimated subcontract costs at $300/lane mile).
- INDOT: $3,747 per lane mile on Interstates; does not include snow and ice removal.
- NCDOT: $3,800 per lane mile on Interstates; includes snow and ice control.

PBC Contract Costs

- FDOT: $5,000 per lane mile; does not include snow and ice control.
- NCDOT: $7,200 per lane mile; does not include snow and ice control.
- VDOT: $10,000–$18,000 per lane mile; includes snow and ice control.

These comparisons can be disputed as not being on equal basis, which is probably true. But you cannot ignore the magnitude of difference between PBC and in-house costs. With this much difference, transportation agencies are not saving money by using PBC contracts.

PBC PROGRAM RECOMMENDATIONS

If an agency decides to pursue PBC for maintenance operations, what is the best way to implement and what are some precautions? The recommendations are as follows.

1. Central office PBS administrator work with ICA to market the concept and develop contractor interest. Survey contractors and develop a list of capabilities that contractors possess for maintenance activities. Analyze what areas of the state would be conducive for implementing PBC

contracts which is dependent on contractor resources and availability. Develop state legislation to get best and final offer contract type approved. This will take lobbying effort and time.

2. After determining the best fit district, select district PBC manager. Central office PBC administrator and district manager select road network to develop contract. Optimum PBC contract length is 120 to 140 road miles.

3. Develop budget for PBC contract and determine where the funds will come from. PBC contracts can cost up to five times as much as in-house costs. Besides contract cost the budget needs to include administration costs, which could be in the range $150,000 annually, the assessment cost (NCDOT is spending $92,500 per assessment), and training costs.

4. PBC team. The PBC administrator and manager needs to assemble a team(could involve up to 10 senior individuals) to develop the following, which will probably take up to 18 months.

- Develop LOS criteria; test and evaluate criteria before using.
- Perform baseline assessment.
- Determine scope of work.
- Develop engineer's estimate.
- Develop contract requirements and bidding documents.
- Develop assessment program. Determine frequency, assessors, inspection tools, and software requirements. Specify confidence level (e.g., 95%) as this will determine the number of inspection segments.
- Develop contract administration guidelines and job descriptions. Select contract manager and assign to the contract development team.
- Develop training program for contract administrator and inspectors, and the assessment program.
- Develop public relations approach targeting current INDOT employees. Internal morale could suffer so measures should be taken to address this issue.

5. Contract requirements:

- Look at other agency PBC contracts.
- Describe the contractor selection procedure.
- Most PBC contracts duration is between 3 to 7 years.
- Describe performance criteria.
- Decide on anti-icing and de-icing activities.
- Determine limits on subcontracts (percent level, e.g. 70%–80%) and inspection requirements of contractor.
- Establish payment penalty requirements. Requirements are needed for the last evaluation period to insure contractor performance.
- Rehabilitation items should not be included in PBC contracts.
- Determine minority participation requirements.
- Make the contract dynamic in that current specs and procedures apply.
- Adequately define responsiveness requirements.
- Include the ability to write work orders to the contractor to assist the agency when additional help is needed.
- Develop report requirements.
- The level of effort at this stage is very important. Since this is a new contract type be careful about requirements and risk allocation. Partnering should be included in the contract.

6. Contract administration:

- Develop inspection procedures

- Implement a partnering arrangement with the contractor
- Establish a meeting pattern with the contractor.
- Comply with reporting requirements.
- Monitor incident response and emergency repairs.
- Evaluate and approve traffic control plans.

Maintenance Plan

Below are recommendations for an agency to consider while analyzing its maintenance plan.

- Private contractors are a viable option.
- If snow and ice activities are the critical ones, develop subcontracts to utilize private contractors.
- Determine maintenance needs and develop a more comprehensive subcontract program. This referred to as a “hybrid approach” where private local contractors are used to supplement agency forces and in some cases work together. Work with your state contractor association to develop this program by growing the amount and number of available subcontractors.
- Identify and inventory activities and compare to availability of private sector entities throughout the state.
  - Mowing,
  - Sign maintenance activities,
  - Road maintenance activities,
  - Bridge maintenance activities, and
  - Road painting activities.
- Risk is the biggest factor affecting contractor pricing. Minimize and share risk.
- An agency needs a LOS requirements description. This helps to establish a baseline and helps to establish budget numbers for higher or lower LOS. This will be necessary for building a request for additional maintenance funds from the legislature.

RECOMMENDATIONS

- PBC will require development time, new organization, capabilities, resources, and training.
- PBC will not save money in most cases. There are some cases where money has been saved through PBC contracts, for example, rest areas, movable bridges, and security contracts.
- Local contractors are interested and capable of performing maintenance activities.
- Current conditions, such as declining income and growing network, require that an agency needs a plan.
- In Indiana, with 1,350 additional lane miles at $4,500 per lane mile (very conservative) equals a $6,075,000 annual increase in operations budget. This will most likely be difficult to obtain.
- Due to economic realities the PBC option has a lower ranking.
- In snow belt states, anti-icing and de-icing subcontracts should be pursued.

- An agency should investigate a “hybrid” approach where in-house forces are supplemented through subcontracts with private contractors. This approach starts with an analysis of contractors and their capabilities and resources by districts. This analysis will reveal what services are available and what services need to be developed.

ACKNOWLEDGMENT

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Results and Lessons Learned from District of Columbia Department of Transportation's Tunnel Asset Management Contract

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The District of Columbia's Department of Transportation (DCDOT) has entered into an asset management contract for the preservation of the District's tunnels, which includes the maintenance, rehabilitation, and management of 17 tunnels in Washington, D.C. This agreement is a 5-year performance-based contract where predefined service levels are established and a private contractor is responsible for maintaining and managing the tunnel assets. These contracts are not new to DCDOT, but can be considered a novel approach as compared to traditional contracts. Many of the tunnels in the District are in need of various levels of rehabilitation and timely maintenance to keep them in good condition and to preserve their value. The tunnel contract includes structural, mechanical, electrical, management, and lighting maintenance categories. The work entailed in this effort is very challenging in terms of project scope, technical requirements, heavy traffic, and resource management and coordination. Regardless, the contract requires a consistent, high level of service to ensure that residents and visitors across the city are well served. Consistent with performance-based contracting, the challenges are balanced by tiered financial incentives and disincentives for consistently meeting or not meeting the level of service requirements defined in the contract. The contract includes 87 performance measures and an equivalent number of time and response measures. The presentation shares information on the performance measures, the performance results to date, start-up considerations, and the lessons learned from an urban performance-based tunnel project.

Bridge Monitoring and Planning

Asset Management Plan for the Ambassador Bridge

MICHAEL F. BRITT
MICHAEL J. BORZOK
Modjeski and Masters, Inc.

Opened to traffic on November 15, 1929, the Ambassador Bridge is an international crossing spanning the Detroit River between Detroit, Michigan, and Windsor, Ontario, Canada. At that time, the bridge's 1,850-ft suspended span was the longest of any bridge in the world. It is owned, operated, and maintained by the Detroit International Bridge Company (DIBC). It is the number one U.S.–Canadian commercial crossing in terms of trade volume, carrying 23% of all surface trade between the two countries. The Michigan Department of Transportation (MDOT), with the support of FHWA and cooperation from DIBC and other local stakeholders, has broken ground on the largest single construction contract that MDOT has ever undertaken, the $170 million Ambassador Bridge Gateway Project (ABGP). The ABGP is a major freeway reconstruction effort that will enhance commercial access to the Ambassador Bridge while improving traffic flow and safety on local roads. The project, which began in the summer of 2007, will include a reconstructed I-75–I-96 interchange with new connections to the Ambassador Bridge Plaza. The DIBC has a long history of aggressive inspection, maintenance, repair, and reconstruction of its Ambassador Bridge transportation asset. Working with Modjeski and Masters, Inc., the DIBC formalized its plan for the continued preservation of the bridge through the development and implementation of an asset management plan. The plan assures MDOT, FHWA, and other interested stakeholders that the structure will continue to be maintained at a level that will be compatible with ABGP and able to safely and efficiently handle any additional traffic that will be generated upon its completion of construction in 2009. The asset management plan for the Ambassador Bridge has been developed with the entire life cycle of the bridge in mind. It is based on guidance issued by FHWA including the Asset Management Primer, dated December 1999, as well as bridge specific documents such as annual inspection reports. It focuses on the existing bridge but takes into consideration that its remaining useful life, until a major rehabilitation is undertaken, may be limited. The plan includes planning, programming, engineering, construction, inspection, maintenance, and operations. It recognizes that continued and sometimes significant investment must be made with respect to a broad set of objectives, including physical preservation, congestion relief, safety, security, economic productivity, and environmental stewardship. This paper and presentation will document the development and implementation of the plan by the DIBC and how its continued implementation facilitates the safe and efficient movement of goods and services between the two countries, enhances tourism, and improves the quality of life in communities near the bridge.

Currently, many transportation systems are reaching the end of their service lives due to increased truck traffic and increased vehicular loading. More owners are taking a hard look at their budgets, the age of their systems, increased traffic demands, and increased loads and are developing new strategies to extend the useful service life of their facilities and get the most out of their transportation dollars. The Detroit International Bridge Company (DIBC), owner and operator of the 79-year old Ambassador Bridge, is doing the same thing. Their solution is an asset management plan that essentially follows the business processes that embody the principles of performance-based planning, programming, and management as promoted by FHWA and AASHTO. This document is based on guidance issued by the FHWA including the Asset Management Primer, dated December 1999.

Essentially, asset management involves taking what is already there, caring for it, upgrading and improving it where practical, and making it last as long as possible. As applied to bridges, this concept means examining an existing bridge and performing all the necessary maintenance and preventive treatments to make it last as long as possible, or until it costs more to keep up than building a new one.

This document outlines the asset management plan of the existing Ambassador Bridge as it relates to the activities being performed by Modjeski and Masters, Inc. It is not meant to be an all-inclusive plan. The DIBC has other projects underway, either in the design or construction stages that may affect access to the existing bridge, improvement of toll facilities, and system and operational improvements. They are not incorporated into this document.

THE AMBASSADOR BRIDGE

Description

Opened to traffic on November 15, 1929, the Ambassador Bridge is an international crossing spanning the Detroit River between Detroit, Michigan, and Windsor, Ontario. The structure is a suspension bridge with a main span that consists of a 1,850-ft stiffened suspended span and unloaded deck truss backstay spans with lengths of 817 ft in Canada and 973 ft in the United States. The current roadway is 47 ft wide and carries four lanes of traffic with an 8 ft wide sidewalk on the West side. The suspended span channel clearance ranges from 135 ft near the towers to 150 ft at midspan.

The main towers are 363 ft measured from the top of pier to the main cable saddle. The center-to-center spacing between the east and west cables is 67 ft. The compacted diameter of each cable is 19 5/16 in., consisting of 37 strands with 218 No. 6 cold-drawn double-galvanized steel wires per strand (8,066 total wires per cable). Refer to Figure 1 for general suspended span details.

In addition to the main bridge crossing, there is approximately 2,410 ft. of approach structure on the Canadian side and 1,430 ft. on the U.S. side. The Canadian approach consists of 42 plate girder spans while the U.S. approach contains 25 plate girder spans with a deck truss span over Fort Street. The approach span roadways are supported by transverse floor joists spaced at 6 ft. on center and setting on top of the simply supported built-up plate girders. Refer to Figure 2 and Figure 3 for a general plan and elevation of the United States and Canadian approach structures, respectively.

Alterations and Repairs

Numerous repairs and alterations have been performed to the Ambassador Bridge since it opened in November of 1929. A summary of the more significant items is presented in Table 1.

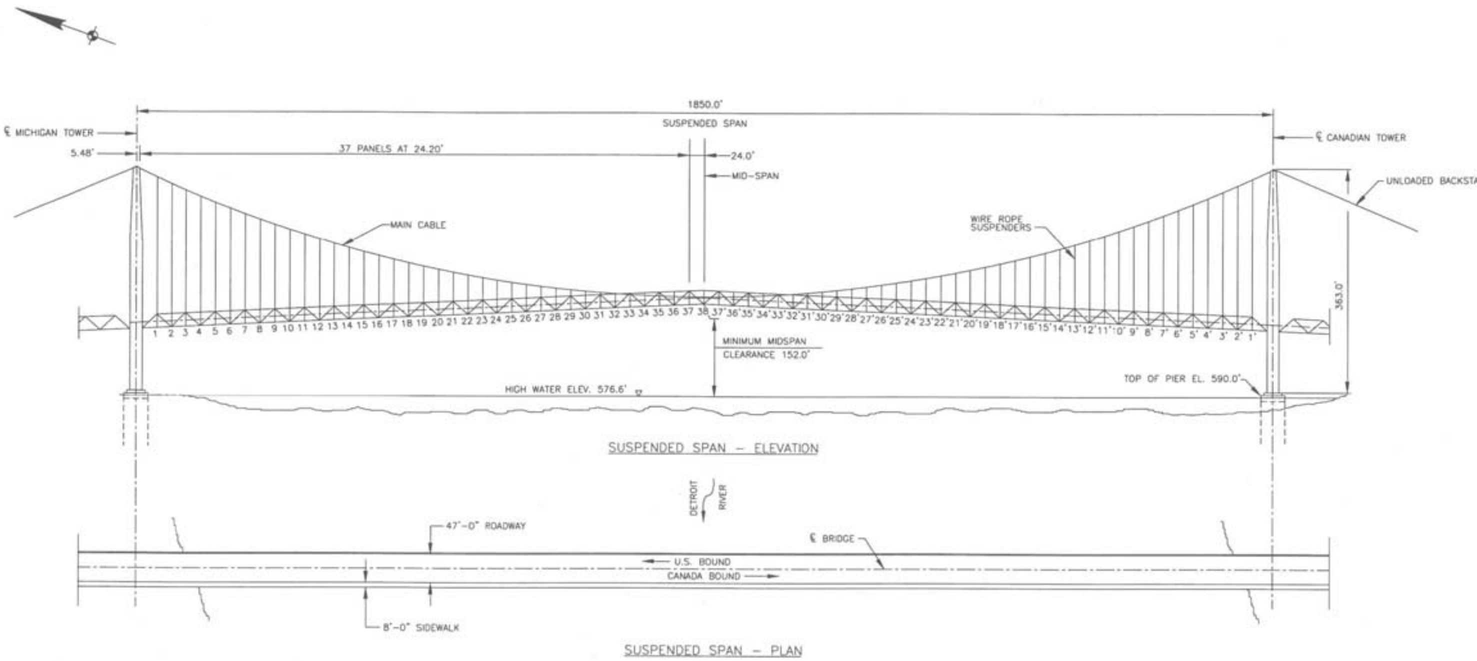

FIGURE 1 Plan and elevation of suspended span.

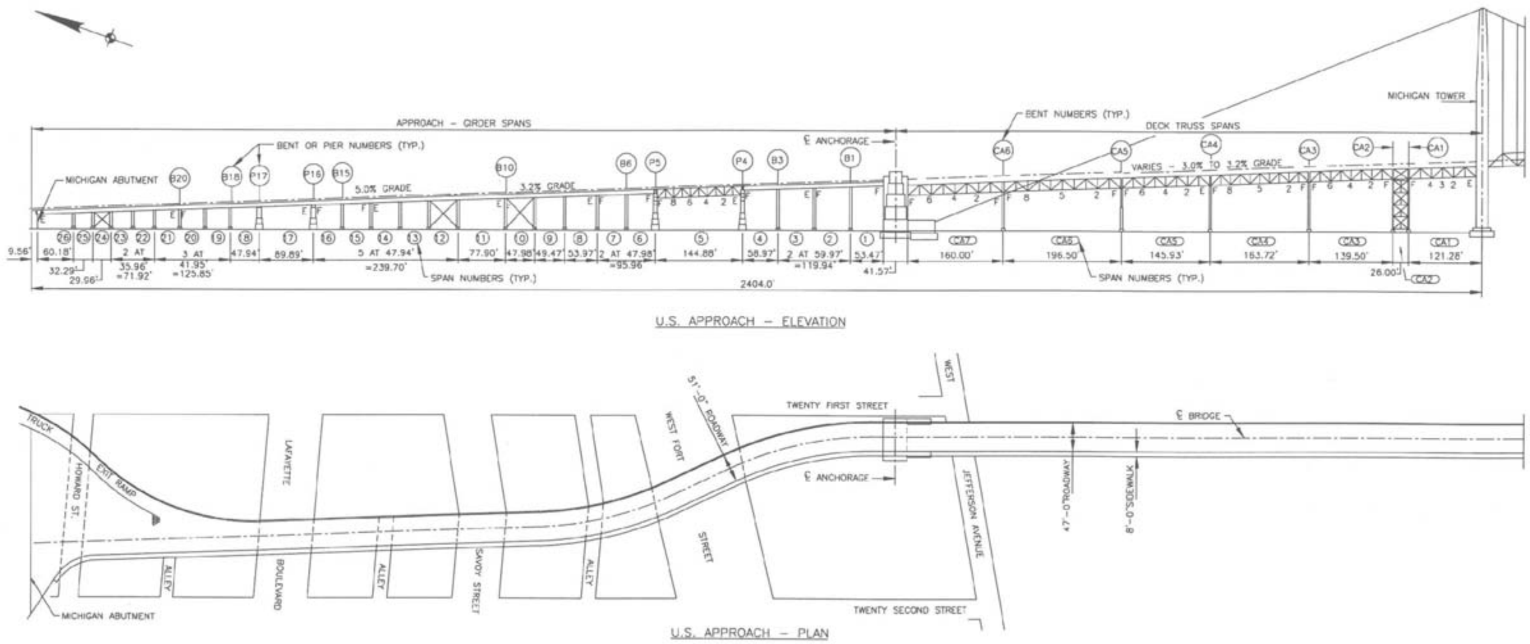

FIGURE 2 Plan and elevation of U.S. approach spans.

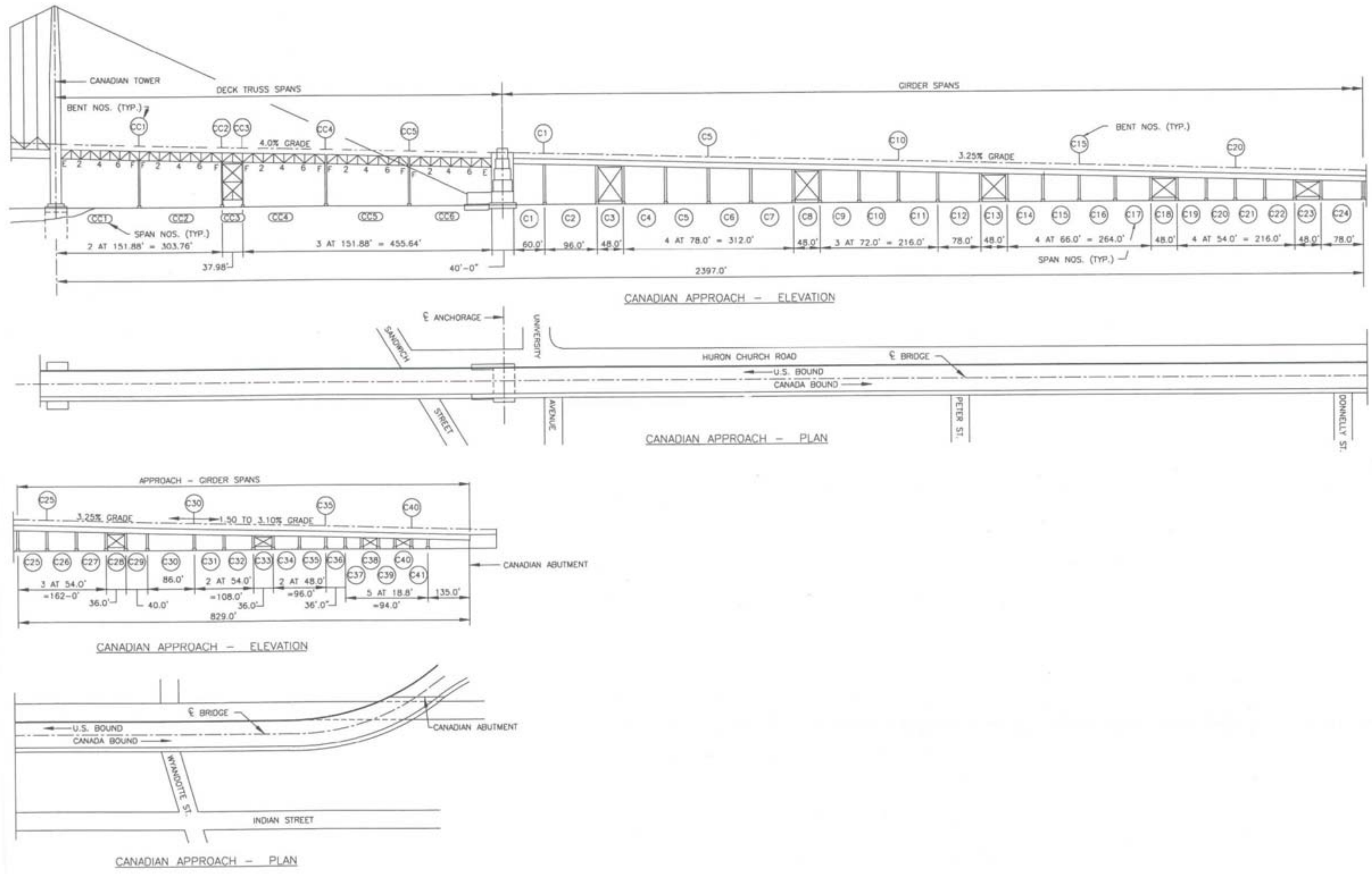

FIGURE 3 Plan and elevation of Canadian approach spans.

TABLE 1 Major Alterations and Repair by Decade

Date	Event
1940s	Entire roadway resurfaced and new sidewalks constructed
1940s	Approach superstructures, main cables, and steel bents partially painted
1950s	Main span stiffening trusses repainted
1970s	Replacement of wearing surface along with full-depth deck repairs on the Canadian approach spans
1970s	Removal of granite wearing surface and placement of asphalt wearing surface on U.S. approach spans
1970s	Curbs and sidewalk replaced on Canadian and U.S. approach spans
1970s	Main towers repainted
1970s	Corrective and preventative maintenance program officially established
1970s	Replacement of all cable band bolts
1980s	Deck replacement on U.S. approach and truss spans
1980s	Rocker links replaced
1980s	Numerous items repainted
1980s	Necklace of lights added
1990s	U.S. plaza expanded
1990s–2000s	Entire bridge blast cleaned and repainted
2000s	Replacement of many expansion joints in approach spans; replacement of selected suspender ropes for evaluation of existing ropes; specifications adopted for washing and paint rehabilitation of structural steel

MODJESKI AND MASTERS, INC.

Modjeski and Masters has been continually working with the DIBC since 2006 on the development, refinement, and implementation of this asset management plan. It may be of interest to the reader to gain an understanding of the capabilities of Modjeski and Masters to develop such a plan for this very important international crossing.

History

Modjeski and Masters' tradition as a leader in bridge engineering dates back to 1893. The firm is one of the oldest consulting engineering firms in the nation. Today, Modjeski and Masters is widely respected for its specialized technical expertise in design, inspection, and rehabilitation of all types of bridges. It has designed eight suspension bridges in its 115-year history and inspected and rehabilitated scores more. Currently, we are providing engineering services for 10 suspension bridge projects.

Experience with the Ambassador Bridge

Modjeski and Masters' initial assignment for the Ambassador Bridge was to act as a consultant to the owner in the approval of all plans specifications and construction activities for the new bridge. This engagement lasted from approximately 1927 through 1930. At that time the firm was known as Modjeski and Chase.

Modjeski and Masters was engaged in the early 1980s to complete an in-depth inspection of the bridge. This was followed by an assignment to develop contract documents for the redecking of the U.S. approach spans and provide associated construction inspection services. In the early 1990s the firm was again engaged to provide inspection services for the expansion joints of the main bridge.

Most recently, Modjeski and Masters is providing annual inspections of the bridge and design and construction support services for the main cable investigation, suspender rope replacement, and structural steel repairs.

OVERVIEW OF ASSET MANAGEMENT IN TRANSPORTATION

Definition of Asset Management

Transportation asset management is a set of guiding principles and best practice methods for making informed transportation resource allocation decisions, and improving accountability for these decisions. The term “resource allocation” covers not only allocation of money to program areas, projects, and activities but also covers deployment of other resources that add value (staff, equipment, materials, information, real estate, etc.). While several of these principles and practices were initially developed and applied within the domain of infrastructure preservation, most established definitions of asset management are considerably broader. The *Asset Management Guide*, recently adopted by AASHTO, defines asset management as:

> ...a strategic approach to managing transportation infrastructure. It focuses on...business processes for resource allocation and utilization with the objective of better decision-making based upon quality information and well-defined objectives.

Asset management is concerned with the entire life cycle of transportation decisions, including planning, programming, construction, maintenance, and operations. It emphasizes integration across these functions, reinforcing the fact that actions taken across this life cycle are interrelated. It also recognizes that investments in transportation assets must be made considering a broad set of objectives, including physical preservation, congestion relief, safety, security, economic productivity, and environmental stewardship.

Summary of Process

Figure 4 illustrates the strategic resource allocation process promoted by the DIBC that embodies the following elements:

- Goals and objectives supported by performance measures are established through the system planning process and used to guide the overall resource allocation process.
- Analysis of options and trade offs includes examination of options within each investment area, as well as trade offs across different investment areas.
- Resource allocation decisions are based on the results of trade-off analyses. These decisions involve allocations of financial, staff, equipment, and other resources to the different

investment areas or to different strategies, programs, projects, or asset classes within an individual investment area.

- Program and service delivery is accomplished in the most cost-effective manner which again involves consideration of different delivery options (e.g., use of contractors, consultants, in-house forces), as well as a delivery tracking process involving recording of actions taken, costs, effectiveness, and lessons learned to guide future activity.
- System conditions and service levels are tracked to see the extent to which established performance objectives are being addressed. This information is used to refine goals and priorities (e.g., put more emphasis on safety in response to an increase in crash rates).

Transportation Investment Categories

In Figure 4, the box labeled Analysis of Options and Tradeoffs shows three types of investment categories—preservation, operations, and capacity expansion. These are defined as follows:

- Preservation encompasses work to extend the life of existing facilities (and associated hardware and equipment), or to repair damage that impedes mobility or safety. The purpose of system preservation is to retain the existing value of an asset and its ability to perform as designed. System preservation counters the wear and tear of physical infrastructure that occurs

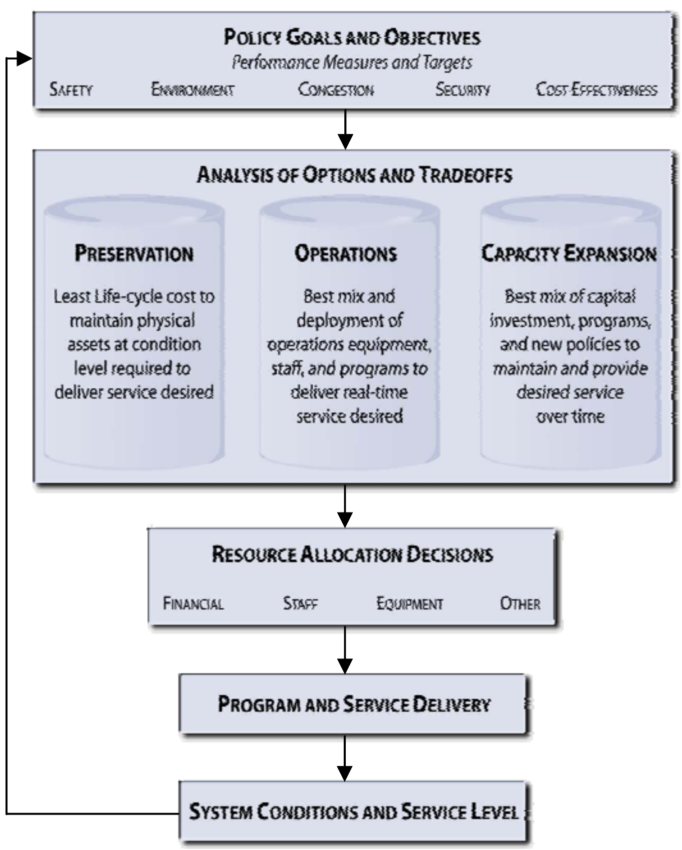

FIGURE 4 Strategic resource allocation process.

over time due to traffic loading, climate, crashes, and aging. It is accomplished through both capital projects and maintenance actions.

- Operations focus on the real-time service and operational efficiency provided by the transportation system for both people and freight movement on a day-to-day basis. Examples of operations actions include real-time traffic surveillance, monitoring, control, and response; intelligent transportation systems; high-occupancy vehicle lane monitoring and control; ramp metering; weigh-in-motion; road weather management; and traveler information systems. Operations will not be discussed in this paper.
- Capacity expansion focuses on the actions needed to expand the service provided by the existing system for both people and freight. Capacity expansion can be achieved either by adding physical capacity to an existing asset, or acquiring or constructing a new facility.

These categories are defined in order to show that

- Asset management is not just about preservation of highway network assets; it is about making investment decisions that address a wide range of policy goals.
- The three categories provide a simple, useful way for DIBC decision makers to align program investment categories and priorities with key policy objectives. For example, many owners have established "preservation first" goals or favor maximizing efficiency of operations prior to investing in new capacity.
- The categories may present alternative ways of meeting a policy goal. For example, it may be appropriate to consider operational improvements to address a congestion problem as an alternative to adding a new lane.
- Decisions about the resources allocated to each category cannot be made independently. Meeting many goals (e.g., safety) may require a mix of investments across these categories. Similarly, an increase in capacity expansion investments may require increased operations and preservation expenditures at some point in time.

As noted above, trade off analysis may be done across investment categories as well as within them. An owner might wish to define investment areas coincident with the categories discussed above, or they may define a different set of categories. For example, DIBC has chosen to redefine the capacity expansion category and rename it as capacity enhancement.

ASSESSMENT OF CONDITION OF THE AMBASSADOR BRIDGE

As mentioned previously, the asset management planning process began in earnest in 2006. The basis, or foundation, of the process was the most recently completed annual inspection of the bridge. Many of the deficiencies and recommendations identified in that inspection report were incorporated into the asset management plan.

The 2006 annual inspection, as performed by Modjeski and Masters, indicated that the Ambassador Bridge was in overall fair condition. There were several structural components that were identified as needing priority attention to improve the overall condition of the bridge. Other items were identified as requiring maintenance work of a continuing nature to be performed annually. The major inspection findings, concerns, and or recommendations for the bridge in general and, specifically, for its major components were as follows:

- The cable system was in need of several specific repairs including the metalwork of the stiffening truss hanger assembly and the gaps in the wrapping wire around the main cables.
- An in-depth cable investigation on the main cables to evaluate the condition of the interior wires was recommended. An in-depth inspection and subsequent rehabilitation, if needed, would help extend the service life of the main cable, a primary structural component of the bridge.
- Many main cable suspender ropes exhibited corroded or several broken wires at the suspender rope socket connections to the floor beams, especially the east cable ropes.
- Corrosion product and staining were observed on the underside of the splay castings and on the outer main cable wires entering the splay castings in each anchorage. Missing and deteriorated caulking at all cable hoods was observed.
- The primary structural metalwork of the suspended main span, truss spans, and girder spans is in fair to good condition; however, several repairs are recommended for these and other components. The major items included: rehabilitating the ends of several stringers in the main span, replacing the severely deteriorated main span floor system metalwork near both towers, replacing the finger dams and the finger dam support metalwork, rehabilitating the stiffening truss link assemblies at both towers, replacing the deteriorated wind transfer plates in the truss span top chords, replacing or repairing significantly deteriorated truss and girder span joists, replacing or repairing the deteriorated truss bracing and connection plates adjacent to the bearings at several bents, and modifying the floor system support metalwork at a limited number of roadway joints reduce vertical deflection.
- There were operational and potential safety problems associated with the inspection and maintenance travelers in the main span.

The condition of the concrete deck of the approach spans has been improved since the 2003 inspection by completing replacement of nearly all of the expansion joints and underlying support joists. The deck of the U.S. truss spans was in generally good condition while the deck of the Canadian truss spans was in generally fair condition. The deck of the U.S. girder spans was in fair-to-good condition while the deck of the Canadian girder spans was in fair-to-poor condition. The main span concrete deck was in poor condition and was nearing the end of its service life. Remedial action was needed on the sidewalk and bridge railings to strengthen against vehicle loading or impact.

The main span maintenance walkway railing may have met past requirements but did not meet the current Occupational Safety and Health Administration standards for guardrail systems.

APPLICATION OF AN ASSET MANAGEMENT PLAN FOR THE AMBASSADOR BRIDGE

The asset management plan for the Ambassador Bridge has been developed with the entire life cycle of the bridge in mind. It focuses on the existing bridge but takes into consideration that its remaining useful life, until a major rehabilitation is undertaken, may be limited. The plan includes planning, programming, engineering, construction, maintenance, and operations. It recognizes that continued and sometimes significant investment must be made to consider a broad set of objectives, including physical preservation, congestion relief, safety, security, economic productivity, and environmental stewardship.

The key stakeholders in the development and implementation of the plan are the management of DIBC and Modjeski and Masters. The plan was supported and reviewed by the Michigan Department of Transportation (MDOT) and FHWA. The plan was undertaken to meet the needs of the Ambassador Bridge transportation facility itself and also the needs of the transportation system in and around the facility.

Again, the asset management plan of the existing Ambassador Bridge relates to the activities being performed by Modjeski and Masters, Inc. It is not meant to be an all-inclusive plan. The DIBC has other projects underway, either in the design or construction stages, which may affect access to the existing bridge, improvement of toll facilities, or system and operational improvements, etc. They are not incorporated into this document.

The asset management plan presented herein focuses on preservation and the possibility of crossing enhancement. Capacity enhancement could simply mean constructing a new facility (e.g., replacing the existing Ambassador Bridge). In a more aggressive interpretation, capacity enhancement could mean adding physical capacity to an existing asset. Both interpretations are accounted for in the plan. The asset management plan for the Ambassador Bridge is presented in flowchart form in Figures 5 and 6.

Preservation

The first portion of the asset management plan focuses on preservation. The Ambassador Bridge is a vital link for heavy commercial traffic and international trade between the United States and Canada. In order to ensure the continued safety and security of this crossing and an uninterrupted flow of traffic and trade across the bridge, the DIBC has allocated substantial capital resources to preserve the structural integrity of the bridge.

As is expected for a 79-year-old structure, the plan emphasizes preservation and encompasses tasks whose purpose is to retain the existing value of the bridge as well as its ability to perform as designed. A two-pronged approach addresses the preservation efforts: bridge inspection and suspender rope and main cable evaluation (refer to Figure 5).

A bridge inspection program is vital to any bridge preservation effort. FHWA requires bridges to be inspected at least once every 2 years in accordance with the National Bridge Inspection Standards (NBIS). The DIBC is inspecting the Ambassador Bridge annually, exceeding the requirements of the NBIS. The bridge inspection is used to identify maintenance and rehabilitation needs. It also serves as the basis for the development of bridge load capacity ratings. Modjeski and Masters was retained by DIBC to perform load capacity ratings for the bridge using the load factor method. The 2005 structural rating of the Ambassador Bridge was submitted to the DIBC in December 2005. An updated report will be submitted in mid-summer 2007.

The rating report identified deficient members and established a basis for the development of repairs of deficient members. The initial set of members identified included those whose rating factor was less than 1.1 at the operating rating. Contract documents for the repair of those members was completed and submitted to DIBC at the end of July 2006. Subsequently, the highly redundant joists were subject to an instrumentation program to

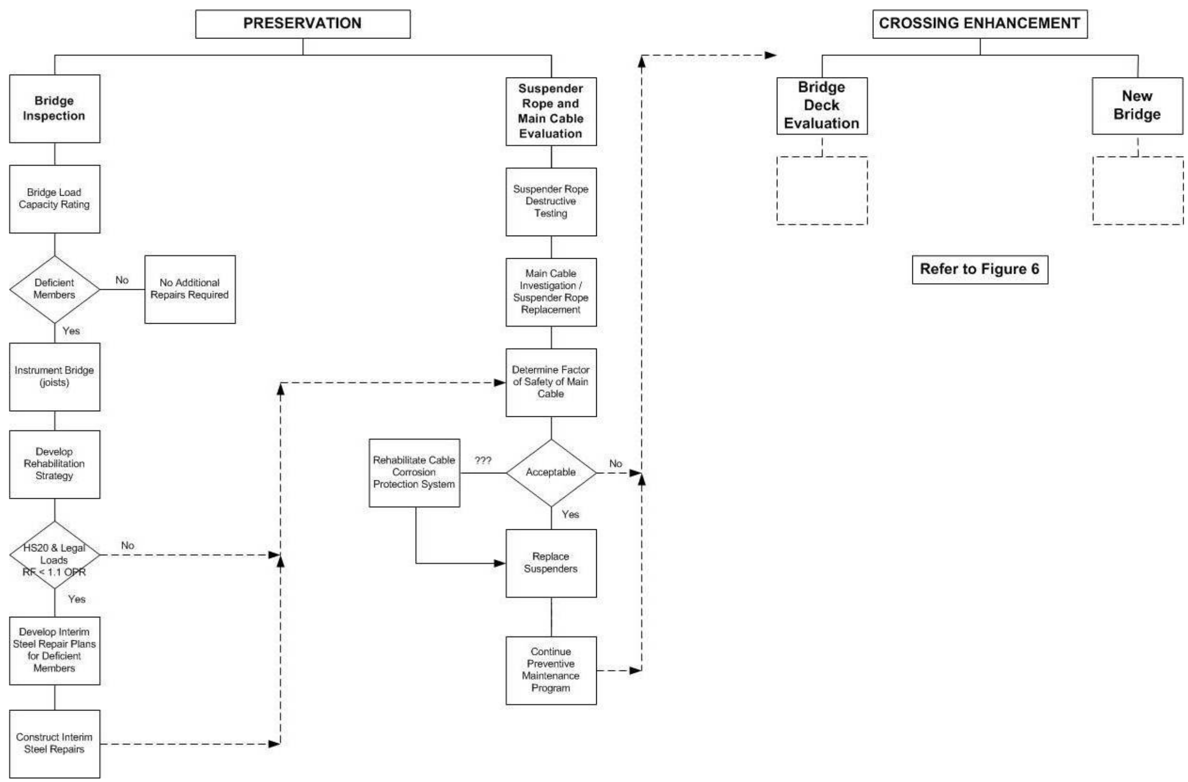

FIGURE 5 Flowchart for asset management plan.

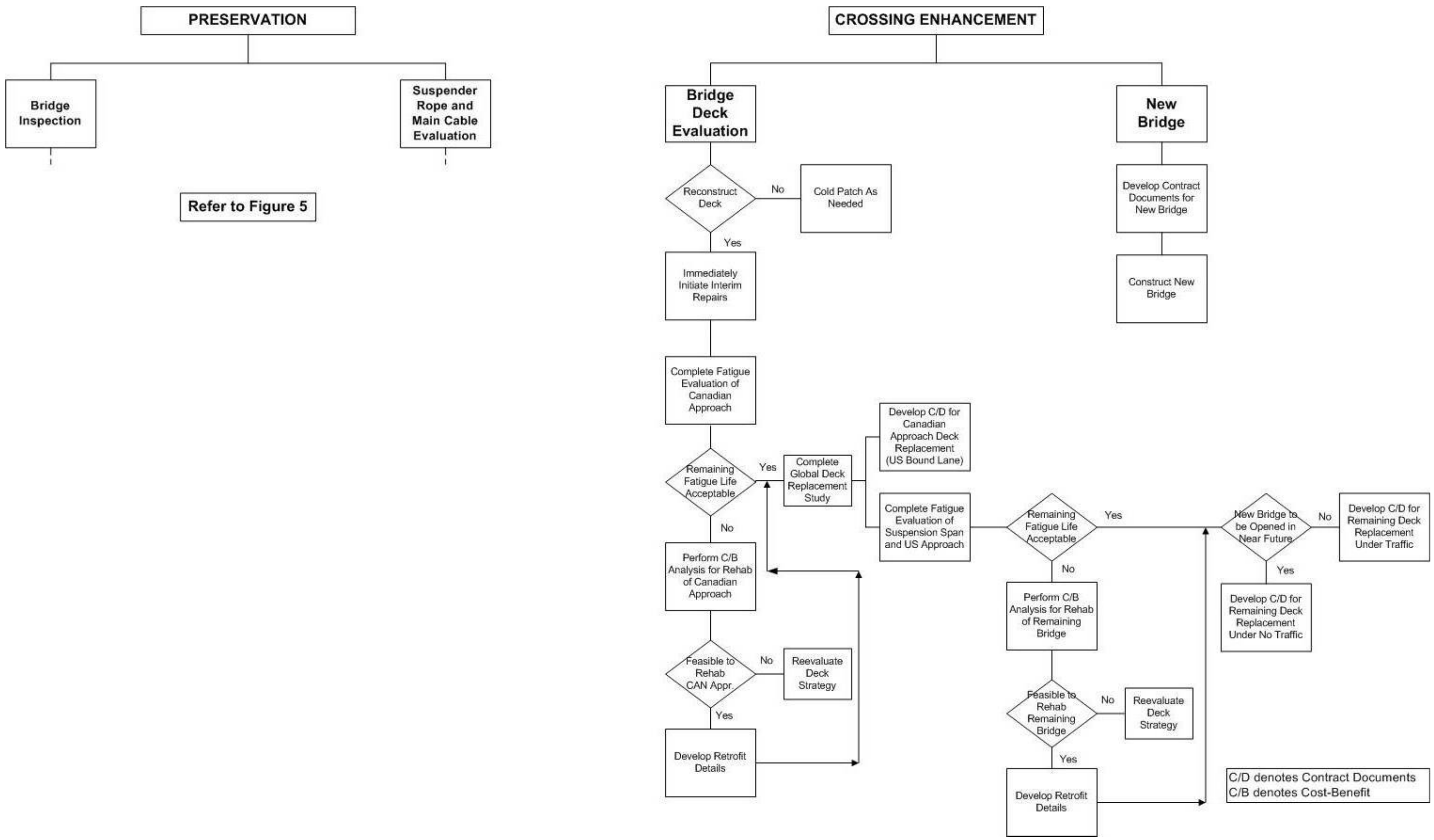

FIGURE 6 Flowchart for asset management plan.

determine if marginally deficient members were actually experiencing the specified live loadings. It was determined that joist live loading, as per the specifications, was conservative. This resulted in the removal from the deficient list of a significant number of joists.

During the same time period, the suspender ropes and main cable were being evaluated. This process began with a testing program of recently removed suspender ropes to determine their factors of safety. The program also identified deficient suspender ropes for replacement. A total of 47 suspender rope pairs were replaced based on the wire break findings during the annual inspections. A final report of the suspender rope investigation was submitted to the DIBC and the field portion of the suspender rope replacement program began at the end of May of 2007 and has been successfully concluded.

The main cable investigation program was developed in accordance with *NCHRP Report 534: Guidelines for Inspection and Strength Evaluation of Suspension Bridge Parallel Wire Cables*. The ultimate purpose is to calculate factor of safety of the cable and determine the acceptability of the factor. This is a major decision point in the asset management plan. A very low factor of safety will have significant impact on the feasibility of rehabilitating the bridge. The field portion of the cable investigation began in July 2006 and concluded in December 2006. A draft report of the findings will be delivered to the DIBC in mid-summer 2007. The result was that the factor of safety appears to be acceptable.

Preventative Maintenance Program

A vital component of system preservation is the implementation of a preventive maintenance program. Preventive maintenance can be defined as the act of keeping a structure in its as-built condition or slowing the inevitable deterioration due to environment, traffic vibration, and deicing chemicals. In some cases, structures are built with flaws such as cracks in concrete which require action to prevent moisture and chlorides from infiltrating the microstructure and causing early deterioration. A structure starts to deteriorate sometimes even before the day its construction is completed, and it is the duty of the owner to slow the deterioration as much as practical using methods and materials that are considered best practices. Only addressing functional or structural needs after the needs have manifested themselves is normally more expensive than proactively implementing a preventive plan or activity on a routine basis. This methodology is similar to keeping a car’s finish waxed or touching up minor scratches or stone chips before the next stage of deterioration which is rust attack. Similarly, at one’s home, it is always cheaper to repair a minor leak in the roof as soon as it is noticed rather than waiting until the underlying roof sheeting is rotted.

DIBC has put in place a preventive maintenance program to allow their facility to function the way it was designed to perform. A listing of the preventive maintenance items is shown in Table 2. Many of these items can be performed by DIBC’s in-house maintenance personnel. Some of the more specialized items, such as cable openings and underwater inspections, would need to be performed by a qualified contractor.

Affordable structural health monitoring technologies are now currently available that allow owners to more clearly understand what’s happening in existing steel and concrete structures. DIBC is considering the use of acoustic monitoring on the main cables and suspender ropes in order to get real-time information on the future condition of these two prime load-carrying members. This technology is very useful for bridges that have known defects and

TABLE 2 Ambassador Bridge Preventative Maintenance Program

Frequency	Preventive Maintenance Item
Annually	NBIS inspection
Every 5 years	Main cable investigation (cable openings)
Ongoing	Structural health monitoring
Annually	Anchorage cleaning
Every 5 years	Underwater inspection of main tower piers
As needed	Debris removal
As needed	Cleaning of drainage system
Annually	Cleaning of abutment tops
As needed	Cleaning of finger joints
Annually	Cleaning and washing of bridge
Annually	Crack sealing in pavement and curblines
Annually	Masonry pointing and crack sealing in piers
As needed	Maintenance of roadway bridge lighting
As needed	Maintenance of "necklace of lights"
Every 3 months	Cleaning and lubrication of wind tongues
As needed	Painting of steel (entire bridge)
Every 3 to 5 years	Spot painting
Annually	Traveler maintenance
As needed	Maintenance of electrical systems
Winter	Snow removal

suspect load-carrying capacity to help optimize life-cycle costs, reduce risks, and develop long-term capital expenditure plans.

Crossing Enhancement

The second major portion of the asset management plan is capacity enhancement. Its major components include a new bridge study, design and construction, and the feasibility of short- and long-term rehabilitation of the existing bridge assuming the preservation legs of the plan have been satisfied.

DIBC has contracted with a consulting firm to develop documents with the purpose of obtaining environmental clearance for the design and construction of a new bridge. DIBC is proposing to construct a six-lane cable stayed bridge over the Detroit River, just west of the existing Ambassador Bridge. The new bridge will connect directly into the existing plazas in both Windsor and Detroit. The new structure will be 102.5 ft wide and 6,200 ft long, with approximately 2,200 ft traversing the Detroit River. No supporting structures (piers and towers) will be placed in the Detroit River. The development of contract documents and construction of the new bridge is independent of any short- or long-term rehabilitation of the existing bridge.

Initially, the feasibility of short-term repairs will be evaluated. Next, the feasibility of rehabilitating the existing bridge will be evaluated. As seen in Figure 6, the major rehabilitation effort will begin with a bridge deck evaluation. To commence this effort, a sequential fatigue evaluation of the superstructure will be undertaken. The intent is to determine the remaining fatigue life of the bridge. Soon thereafter a global deck replacement study will be undertaken.

Should the remaining fatigue life be acceptable or if minor rehabilitation of the fatigue prone details is necessary, a sequential deck replacement program would be undertaken. The replaced deck would include the same number of lanes as the existing bridge; however, lane and shoulder widths would be improved. The feasibility of deck replacement is the next major decision point in the plan. The big question is can the existing bridge deck remain serviceable until the new bridge is opened. Or, if the permitting process becomes lengthy, what staging is necessary for the redecking of the existing under traffic prior to the construction of the new bridge. Both scenarios are woven into the plan. The plan also considers alternative options if the bridge or major components of the superstructure have a very limited remaining fatigue life. This finding will also have significant impact on the feasibility of rehabilitating portions of the bridge.

Should it be feasible to rehabilitate the existing bridge, it would ideally be rehabilitated after the new bridge is opened to traffic. Rehabilitating the existing bridge after opening the new bridge is fairly straightforward. Contract documents for rehabilitation could be developed during the construction period of the new bridge. The rehabilitation contract could be let near the end of construction of the new bridge. Construction activities associated with the rehabilitation would commence sometime after the new bridge is opened to traffic. This would be the best possible scenario for all stakeholders.

Access Improvements

Improving access to the existing and proposed bridges is also an emphasis area for DIBC. On the U.S. end of the bridge, DIBC has entered into a public–private cooperative effort to improve access to the Ambassador Bridge. This project is known as the Ambassador Bridge–Gateway Project. This project specifically addresses the need for long-term congestion mitigation and direct access improvements between the Ambassador Bridge and Michigan's trunk-line highways, which include I-96 and I-75 of the Interstate system. MDOT will be letting a project for the construction of this link. DIBC has hired an engineering consultant to develop a set of contract plans for performing alterations to their facility to dovetail with the MDOT's gateway project.

On the Canadian end of the bridge, the DIBC is in the process of expanding the customs plaza in the area of Huron Church Road. They have contracted with a consultant to provide engineering services for the design of a new ramp as part of this expansion.

SUMMARY

The DIBC has been collaborating with Modjeski and Masters for several years to develop, refine, and implement this asset management plan. Significant resources have been dedicated to seeing this plan through to fruition including financial and in-house consultant and contractor staff. The plan has been developed around the guidance offered by the FHWA and AASHTO. Resource allocation decisions are based on an explicitly stated set of goals and objectives—to cost effectively maintain the safety and security of the facility while minimizing congestion. It is performance based utilizing information from a number of activities such as annual bridge inspections, cable and suspender rope investigations, and load capacity ratings. Decisions are based on quality information and analyses of options and tradeoffs. Performance results are monitored to provide clear accountability and feedback. For example, factors of safety of the main cable and suspender ropes have been used to justify necessary repairs and the completion of repairs is observed and monitored for compliance with specifications. These core principles are the basis of the asset management plan.

The plan has four legs: two dealing with preservation and two dealing with enhancing the crossing. The initial preservation leg, bridge inspection, has been completed with the construction of the interim steel repairs. The second preservation leg, suspender rope and main cable evaluation, has been successfully traversed with the completion of the main cable investigation completed and the suspender rope replacements. The two legs of the crossing enhancement are underway with the completion of the new bridge study, the conclusion of the permitting process, and the initiation of the fatigue evaluation of the Canadian approach structures. DIBC has taken a sound and aggressive approach in the development and implementation of this asset management plan.

ACKNOWLEDGMENTS

The authors thank Dan Stamper, President, Detroit International Bridge Company, and two of his key staff, Dan Reaume and Ken Carter, for their perseverance, cooperation, and open-mindedness in the development of, and commitment to, this asset management plan. Despite the fact that the Ambassador Bridge receives no federal funding, DIBC continues to provide the funding necessary to maintain and improve this facility to safely and efficiently handle the traffic demands of the number one U.S.–Canadian commercial crossing.

REFERENCE

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BRIDGE MONITORING AND PLANNING

A Wireless Sensor for Monitoring Chloride Ingress in Concrete

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Sensors for monitoring corrosivity in concrete that are miniature, wireless, and embeddable, are now a reality. Made using emerging innovations in electronics, and reliable and well-tested electrochemical techniques, our embeddable sensors are durable and accurate. We have built and validated them against bench-top commercial instruments. Called the smart aggregate, the sensor includes both the sensing elements and the electronics for measurement and data transfer, all within a small volume of 1-inch-diameter and ½-in. tall, hermetically-sealed ceramic housing. Some of the early prototype sensors capable of measuring temperature and conductivity are currently embedded in bridge decks in Maryland. More recent embodiments are capable of monitoring corrosivity are described in this document.

Steel reinforcing bars in concrete bridge decks are known to corrode for a wide variety of reasons (*1*,*2*). Figure 1 shows a collection of factors, physical and chemical, affecting rebar corrosion. After the unfortunate collapse of the bridge on I-35W in Minneapolis (*3*), there is an increased awareness of the decaying highway infrastructure around the nation. Rebar corrosion, generally speaking, does not cause catastrophic failure of bridge decks; there is no evidence relating the collapse of the bridge on I-35W to corrosion of rebars. However, rebar corrosion tends to separate the rebar from the mortar, progressively weakening the deck until the bridge becomes unusable. Therefore, sensors monitoring a bridge deck for corrosivity could serve as an early warning system, facilitating less expensive remediation modalities. This paper provides an account of some of the recent advances made in our laboratory in the area of wireless, miniature, embeddable corrosivity sensors called smart aggregates that are being developed and tested in a few bridges across Maryland.

There have been numerous attempts around the world to develop sensors for monitoring bridges and other large structures (*4*). A concise account of embeddable sensors in concrete is found in a recent book by Broomfield (*1*); it includes reference electrodes (measures corrosion potential, E_{corr}), electrodes for electrical resistance measurements (measures conductivity of concrete), galvanic corrosion cells, and electrodes for monitoring polarization resistance (R_p, related to corrosion rates) as embeddable sensing elements. Sensors such as the ones described in Broomfield (*1*) and *Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2007* (*4*) have certain practical limitations. They require wires or cables running through concrete and periodic cleaning and electrolyte replacement. In spite of these limitations, there is a real advantage to using them, especially the ones that measure E_{corr} and R_p. They provide a measure of corrosion caused by the combined effect of all the agents in concrete,

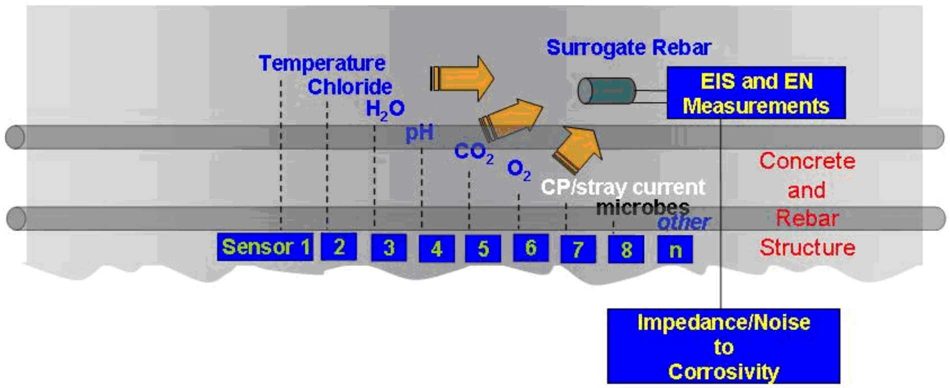


FIGURE 1 Factors that are generally known to influence corrosion of rebars embedded in concrete are shown schematically. There have been several attempts to develop and use embeddable sensors to monitor chloride, pH, humidity, etc., to monitor and follow the corrosivity of concrete. An alternative approach is to use surrogate rebars as sensors, and monitor their corrosion as an indicator of the corrosivity of concrete. In all cases, the size, power consumption, mode of data transfer, and longevity are critical aspects of the sensor design.

not just a single one. This approach is much more practical than the alternative of having individual sensors, one for each agent (Figure 1), and then somehow attempting to predict the effect of each on corrosion. With the evolution of ever-shrinking and lower power electronic components, the R_p-type sensors can be made wireless and completely embeddable without the need for batteries or wired connections to the outside world. When appropriately tooled, they can also be reasonably accurate in estimating the corrosivity of concrete.

DESIGN CRITERIA FOR SENSORS MONITORING CORROSIVITY IN CONCRETE

It is now commonplace for sensors to be miniature, wireless and carry an electronic ID number. The critical design factors for embeddability, though, are

1. The sensing elements that should remain free of maintenance;
2. Miniature instruments to measure corrosivity, corrosion rate, etc.;
3. Battery- or cable-free power for operating the embedded instrument and transmitter; and
4. Life expectancy for the entire unit, including the sensing elements and the electronics that is comparable to the life of the structure being monitored.

Steel as a sensing element is compatible with concrete; once embedded, it lasts as long as the rebars and requires no cleaning during its service life. It is ideally suited for two widely used techniques: AC impedance, also known as electrochemical impedance spectroscopy (EIS), and electrochemical noise (EN) measurements. Their sensitivity to corrosive agents such as salt is adequate: according several earlier reports (*5*,*6*), the maximum recommended Cl limit is 1 lb per cubic yard of cement, an equivalent of 11 mM in water. The Maryland State Highway Administration (MDSHA) uses the criteria that chloride ions (Cl) in excess of 33 mM leads to extensive corrosion. Using these criteria, we have designed sturdy, long-lasting sensors that operate on just mWs of power.

The smart aggregate has built-in instrumentation for conducting EIS, which is one of the most powerful and versatile tools available to measure corrosion rates and monitor corrosivity. EIS utilizes a very small perturbation ac current signal (1- to 3-$\mu A/cm^2$ amplitude, and 15 to 20 different frequencies applied simultaneously); the measurements are conducted at or close to E_{corr}, and the technique is essentially nondestructive. In the past, the complexity, cost, and sophistication of the instruments had limited the widespread application of EIS. Within the last decade, electronic hardware manufacturing industry, aided by the demand for multifunctional, multimedia devices (cell phones and iPods), has revolutionized programmable miniature electronics to commercial, off-the-shelf, affordable, high-fidelity, and versatile levels. Adapting these new innovations into EIS, and incorporating stable sensing elements, chemical-resistant housing, and hermetic sealing to the design provides an embeddable sensor that is accurate, cheap and has a life expectancy that can be in excess of the life of the structure.

The EN implementation, also built into the smart aggregate, measures the electrochemical current noise that is intrinsic to the sensing elements; it does not perturb them with external current or voltage signals. The instrumentation is essentially a zero-resistance ammeter (ZRA).

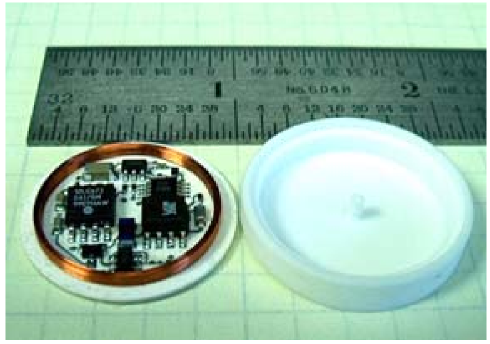
Besides the cost and wireless aspects, our embeddable sensor is also user-friendly. First, the perturbation, response measurements, and the analysis capabilities reside in the sensor itself, so almost anyone with a little training could make the measurement and obtain the end results. The built-in ID allows the user to have multiple sensors in a single structure, and not have to worry about data mix up. Users are free to choose their own procedures and protocols for data transfer and down-the-line use. It also comes with complimentary devices such as embedded temperature sensors; additional features can be augmented with ease. The sensor described in this work has the potential to match a number of industries' requirements described in a recent article (*7*).

THE WIRELESS MINIATURE EIS–EN SENSOR

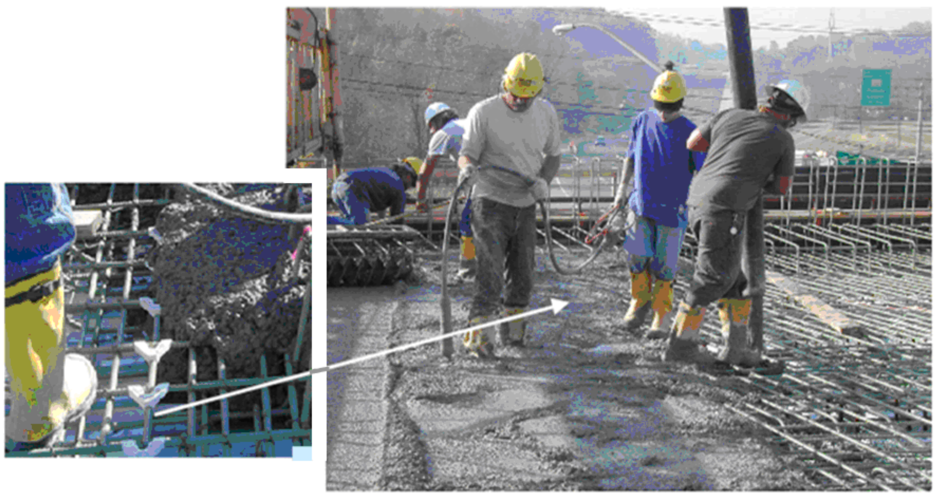
Figure 2*a* shows a photograph of a prototype miniature wireless sensor made for encapsulation and embedding in concrete. The process of installing the sensor in rebars in a bridge deck is shown in Figure 2*b*: it consists of a sensor holder (made of polyurethane that snap fits onto the rebars) with a recessed cavity into which the sensor snap fits. Figure 2*c* shows the process of pouring concrete over the sensors. Currently, we have about 20 such sensors, capable of making temperature and conductivity measurements, embedded in three bridges in Maryland.

Power

The sensor contains no battery for power; it is powered by an induction technique by placing a coil carrying an electric current a few inches above the concrete surface. A smaller coil in the embedded instrument (seen in Figure 1*a* around the circular periphery of the instrument) is



(a)



(b) **(c)**

FIGURE 2 (*a*) A 1-in. diameter embeddable corrosivity sensor that operates entirely in wireless mode. This sensor measures temperature and electrical conductivity. (*b*) The sensor is installed using V-shaped holders that snap-fit onto rebars. (*c*) Concrete is poured over the sensors following conventional procedures used in the absence of sensors, and virtually every sensor survives this process.

inductively coupled to the driving coil and powers the instrument. The power consumed by the sensor during each measurement is about 6-mW; it takes less than 100 s to complete a single set of measurements.

Electronic Noise

The footprint of the instrument is quite small such that the pickup of electrical noise from the environment is minimal. Furthermore, as the length of the wires (cable) between the instrument and the sensing element is small (~1-mm), there is also little noise pickup by the wires.

Life Expectancy

In general, the life expectancy of embedded sensors may be limited by corrosion-related damage to the electronics, loss of sensing elements, and if powered by batteries, by the life of the battery. As the smart aggregate is not battery powered, its life is not limited by the battery. The electronics are housed in hermetically-sealed ceramic, which prevents moisture or other vapor intake, and it is expected to survive well past the life of most bridge decks.

Measurement Time

In the EIS versions, the time required for a measurement is determined by the lowest frequency (0.05 Hz) of the impedance spectrum. Measurement at 0.05 Hz is repeated through two full cycles, (and averaged), which takes 40 s to complete. Measurements at higher frequencies are completed within the same 40 s. Thus, the total time taken to complete one EIS measurement is 40 s; however, as the measurements are made twice per set, one on the internal standard (an RC-circuit described in Figure 3*a*), and two on the sensing element, the total time doubles to 80 s. Adding 15 more seconds for data analysis and transfer, the total measurement time is 95 s. For the EN part of the sensor, the duration is 100 s, at the rate of 0.1 s per data point (10 Hz rate); the collection rate and the duration can be modified according to the field of use. Temperature measurement, typically, is a single-point measurement, and takes a fraction of a second.

Limitations

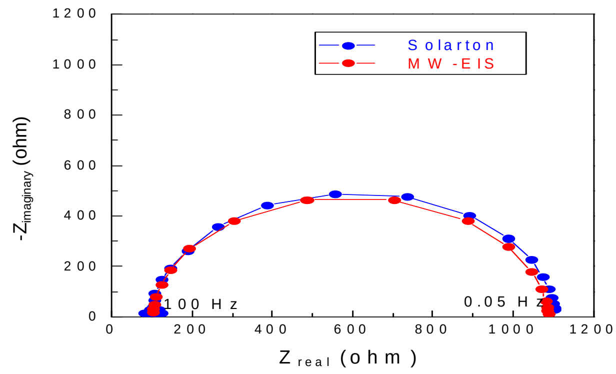
One of the limitations of the EIS part of the sensor is the frequency range over which it makes measurements, which is 0.05 to 100 Hz. This is a narrower range than the ideal range of 1×10^{-4} to 1×10^{6} Hz used in laboratory studies, and recommended by books and other reputable publications (*8–11*). In the smart aggregate, the upper frequency region limit (100 Hz) is due to present power and space limitations. It is anticipated, however, that this upper limit will shortly be increased to at least 1,000Hz. The lower frequency region (<0.05 Hz) is not due to the instrumentation limitation, but the time required to complete one set of measurement as described above. If system is stable over periods in excess of several minutes, the instrument can be programmed to operate at lower frequencies.

RESULTS AND DISCUSSIONS

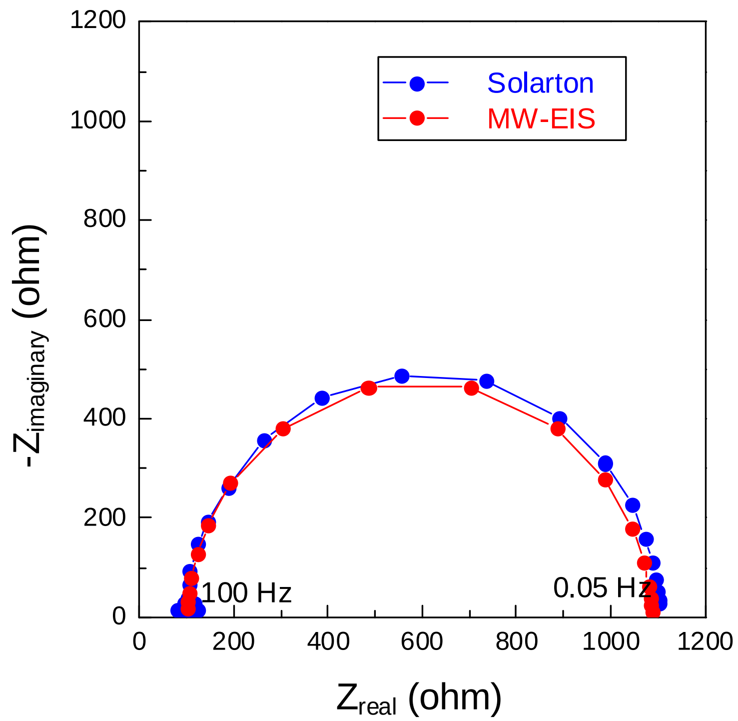
EIS Data from the RC-Circuit

A typical electrochemical interface is represented by an RC-circuit such as the one shown in Figure 3*a*.

The EIS response of the RC-circuit plotted in the so-called Nyquist format in the shape of a semicircle (Figure 3*b*) helps to elucidate the procedure in determining R_{conc} and R_p (*7–10*). The EIS data in the figure were obtained using the EIS part of the smart aggregate and a bench-top EIS instrument, Solartron SI 1287/SI 1250. The two sets of data match fairly well, demonstrating a comparable quality of performance between the smart aggregate and the bench-top instrument



(a)



(b)

FIGURE 3 (*a*) The RC circuit used in testing the MW-EIS sensor, with R_{conc} = 2.8 kohm; R_p = 6.8 kohm; and C_{dl} = 4.7 µF. (*b*) The Nyquist plot of the RC circuit as measured by the MW-EIS sensor (red) and a bench-top EIS instrument (blue).

Furthermore, if the RC-circuit in the figure were a corroding electrode, then the diameter of the semicircle (R_p) would correspond to the polarization resistance, from which corrosion rate could be computed. Note that the RC-circuit in Figure 3*a* is a standard internal calibration unit built into the smart aggregate.

EIS Data from Concrete

The results reported below were collected using sensing elements that were embedded in several concrete blocks. The instruments, though miniaturized, were not embedded, but remained outside the blocks. Each sensing element was a 0.3175-cm-diameter carbon steel rod (working electrode, WE), set in epoxy exposing only a circular disc area at the top. It was positioned concentrically inside a 1.0-cm-diameter (inner) stainless steel tube (counter electrode, CE), with the WE surface recessed below the lip of the CE, and the space above the WE filled with a mortar-water paste. The area ratio between the WE and CE was about 1:10. The resulting electrochemical cell is shown in Figure 4.

After the mortar cured, the cell was embedded in concrete such that there was ½-in. concrete cover above the surface of the cell. The concrete was a commercial brand Quikrete, which was mixed with the manufacturer-specified amount of deionized water, and cured for 30 days before testing. Six such concrete slabs with multiple cells were prepared. They were divided into three sets of two slabs each, and each set exposed to deionized water containing 0, 30, and 100 mM equivalent of dissolved sodium chloride, respectively. AC impedance data measured using a amart aggregate and the bench-top EIS instrument are shown in Figure 5. As in the RC-circuit case (Figure 3), the two sets in concrete also match fairly well with each other. The corrosion rate (CR) values of the WE (carbon steel) computed from R_p, at various intervals of exposure of the slabs to Cl, are shown in Figure 6. They indicate an increase in CR with increase in Cl concentration, but only when the concrete is wet. When the concrete is dry, the corrosion rate for steel tends to be relatively small even in presence of Cl in the concrete.

FIGURE 4 The sensor showing the stainless steel counter electrode (CE) and the mortar. The working electrode (WE) is a 3-mm-diameter steel disc, placed concentrically with the CE; the surface of the WE is located about 0.6 cm below surface of the mortar.

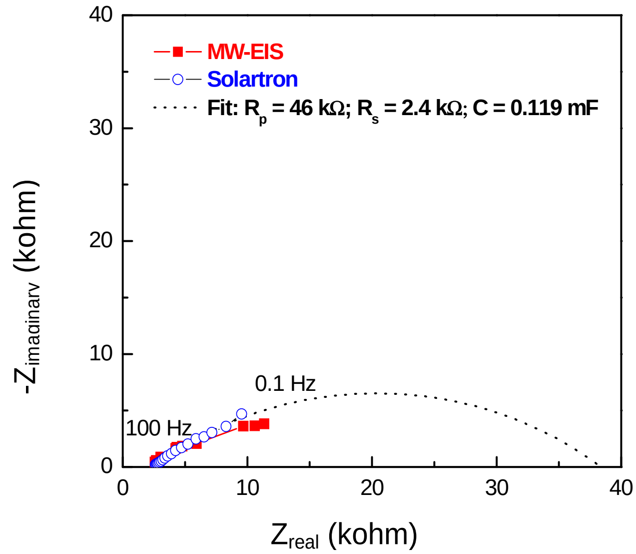


FIGURE 5 The Nyquist plot for carbon steel in concrete in contact with sodium chloride (10-mM)—red: Miniature Wireless EIS (MW-EIS) Sensor; blue: Bench-top EIS instrument. The dotted lines correspond to fitting of the experimental data.

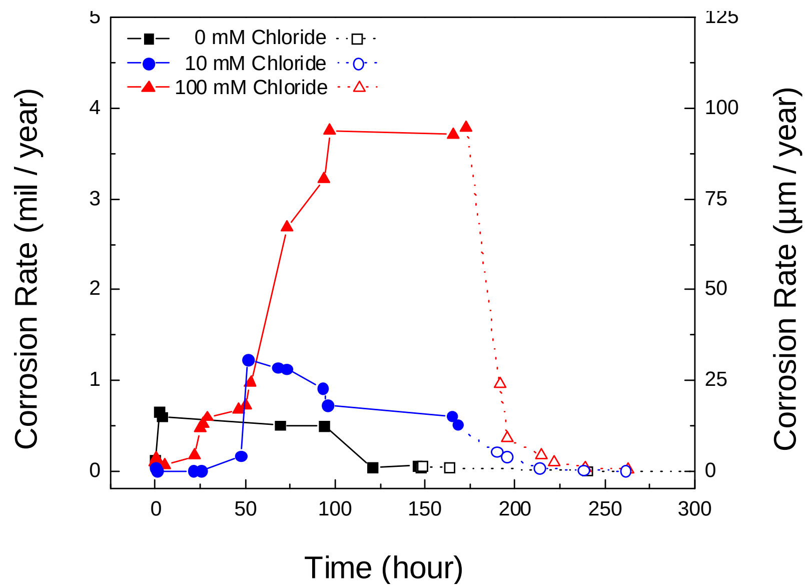


FIGURE 6 The corrosion rates versus time of immersion for cast iron in concrete that was in contact with water containing various concentrations of sodium chloride. The solid points correspond to the data when the concrete was wet; the open points, when the concrete was drying.

EN Data from Concrete

EN Measurements

The EN measurements also used the same type of cell and concrete slabs as in the EIS case. However, the concrete used in making the slabs were obtained from a source that supplied concrete for constructing bridge decks; the slabs were cured first for 30 days.

Twelve concrete slabs with two cells in each were prepared and divided into four sets of three each, and each set was exposed to deionized water containing 0, 10, 30, and 50 mM dissolved sodium chloride, respectively; there were six sensors at each concentration of Cl. Over the next 600 hours, EN current measurements were repeated in intervals of 2 h for each slab; 100-s of the EN current signal from each measurement was averaged into a single value, I_{ave}. The highest and lowest I_{ave} from the six sensors in each set were rejected; the mean and standard deviation of the remaining four I_{ave} values were computed as the average current, Î.

Here is a note that will be further elaborated in the following section on Concurrence Between Lab Test Results and Field Data: when we collected the concrete at the construction site and made the slabs, we did not have a priori knowledge about its pH and chloride content; the concrete was presumed to have little or no chloride, and its pH above 12. This turned out to be not the case (results are reported in the following section), when we cored the concrete from the deck, and tested it for chloride and pH; however, these tests were conducted long after the lab-based EN measurements were completed.

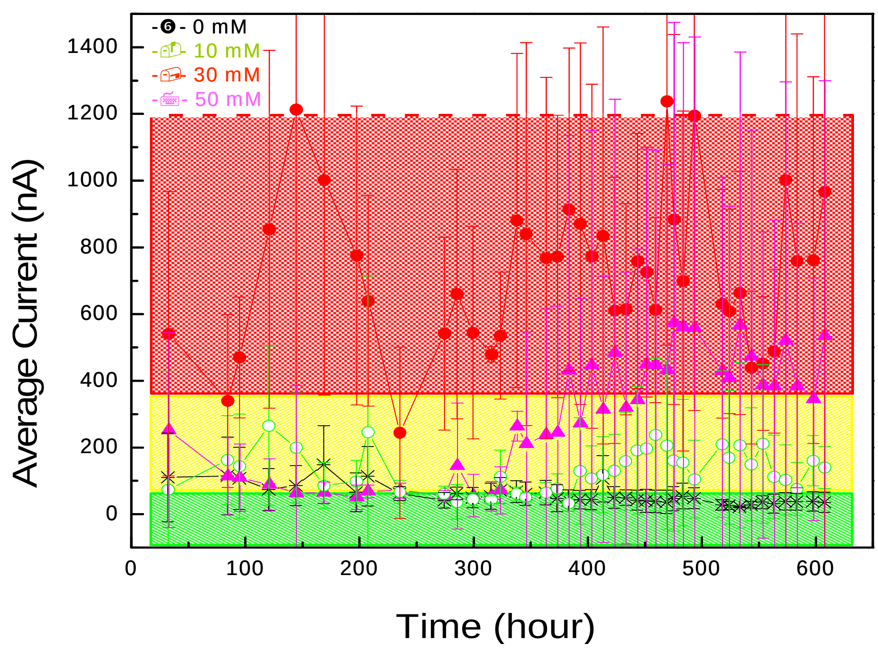


FIGURE 7 Average current outputs (Î) of the chloride sensors embedded in concrete and exposed to 0, 10, 30, and 50-mM salt water. Each point in the graph represents average outputs of four sensors, and bars represent the standard deviation.

The average current, Î for all the four Cl concentrations collected over 600 h are shown in Figure 7. As stated earlier, Î is the average current of four sensors; the bars represent the standard deviation. Over the first 300 h, the Î values remained below 150-nA in most cases, except in the 30-mM case, and less frequently in the 10-mM case. During the same period, the standard deviations were quite small in all cases, except in 30-mM chloride. After 350 h, the Î values and standard deviations were consistently small (75- to 150±10-nA) in 0- and 10-mM chloride, and above 500±500-nA in 30- and 50-mM chlorides. The larger Î values and standard deviations at higher concentrations of Cl are indeed expected behavior of steel in concrete (*12*). Since the sensing element in our EN sensors is the same type of steel as in rebars, they seem to respond appropriately to various levels of chloride.

Concurrence Between Lab Test Results and Field Data

The 500 nA EN current response for the carbon-steel sensing element of geometric area 0.08 cm^2 (6 $\mu A/cm^2$) in concrete exposed to 30 and 50 mM chloride solution is rather high, and was not entirely expected. Even the 1 to 1.2 $\mu A/cm^2$ currents for the carbon-steel sensor in concrete exposed to de-ionized water (no dissolved chloride) was exceptionally high for normal concrete. Such high values may only be expected if the concrete mix itself had large amounts of chloride, and/or if the pH of the concrete was too low. The generally accepted relationship for determining the threshold limit for chloride vis-à-vis pH is $[Cl^-] = 0.6\ [OH^-]$; as the pH of concrete lowers, it is easier for steel to corrode in presence of smaller concentrations of chloride.

When the analysis of the EN current data was completed, the concrete deck that used the same concrete mix as the concrete blocks used in the laboratory for collecting the EN data, had been in use for nearly 12 months, and had gone through one winter, and corresponding exposure to weather and salt. Nevertheless, after the 12 months of exposure, we cored two samples from the deck and analyzed them for chloride and pH at depths of 1, 2, and 5 in. The results showed a wide range of chloride concentrations: 0.8 to 3.1 lb/yd^3, mostly around 1 lb/yd^3; and a wide range of pH: 11.2 to 12.2, mostly around 11.7. The chloride concentrations were higher than the generally accepted limit of 1.0 lb/yd^3,(*5,6*) and the pH was lower than the 12 to 13 range. At pH 11.2, even 1/10th of 1.0 lb/yd^3 chloride would have been adequate to corrode steel. The wide variations in the pH and $[Cl^-]$ in the original concrete mix may therefore explain the large larger Î values and standard deviations observed in 30-mM chloride (Figure 7). In short, while the observed currents were higher than that expected for freshly cured concrete unexposed to brine, the EN test results were consistent with the subsequent analysis of the core samples from the deck.

CONCLUSION

The smart aggregate is a miniature, wireless sensor that is embeddable in concrete, and capable of monitoring corrosivity over long periods of time. It is a single unit that has sensing elements, typically steel, and instrumented with EIS and EN circuitry. It has built in capability to measure temperature and electrical conductivity. Its performance is comparable to commercial bench-top equipment. Its battery-free operating capability and hermetically-sealed ceramic housing gives a longevity of 80+ years that is potentially in excess of most concrete structures. The early prototype versions of the smart aggregate equipped to measure temperature and conductivity have been embedded and tested with success in bridge decks in Maryland. More recent versions capable of monitoring corrosivity through EIS and EN measurements are described in this document.

ACKNOWLEDGMENT

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Pavement Performance
and Preservation Programs

Long-Term Performance of Failed Flexible Pavements Stabilized with Cement

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Lately, there has been a shift in resources away from the construction of new roadway networks to the maintenance and rehabilitation of secondary, low-volume roadways. The focus today is how to achieve a strong and durable pavement that is not only cost effective but also utilizes less virgin materials and is environmentally sustainable. The repair of failed flexible pavements—which make up the majority of most systems—is often an expensive process, especially if the pavement has base or subgrade problems, and a simple overlay will not result in a long-term solution. A procedure is available, called full-depth reclamation (FDR) with cement, which allows old deteriorated asphalt pavements to be recycled and stabilized with cement, creating a new base that will provide an excellent foundation for long-term pavement performance. The concept of recycling existing pavement materials is especially attractive in locations where quality aggregates may not be readily available. Recent studies have shown that agencies have successfully used the FDR with cement process for more than 25 years, with little or no evidence of structural failure in these FDR sections. Cost savings between 30% and 60% and environmental benefits result from use of existing pavement materials, reduced hauling associated with removing old materials and placing new materials, and from the longer expected life of a pavement with a cement-stabilized base. This paper will include the engineering and construction steps involved in designing and building an FDR project, with examples of successful projects constructed over the past 25 years in challenging environments.

Axle loads on streets and highways have increased significantly over the years, while funds for road maintenance have shrunk. Most public agencies have existing road networks comprised primarily of flexible pavements. Progressive public officials looking to save time, materials, and money needed to provide a safe and efficient road network are making it their top priority to salvage these existing flexible pavements at the end of their service lives. Long-term rehabilitation solutions to failed asphalt pavements include a thick structural overlay or complete removal and replacement of the existing base and asphalt surface. Both methods can be extremely expensive and wasteful of virgin aggregates.

A third choice exists where these failed asphalt pavements that no longer provide economical long-term performance can be rehabilitated by pulverizing and stabilizing the pavement structure. A process called full-depth reclamation (FDR) with portland cement can provide the benefits of reconstruction without the substantial costs and environmental concerns. This procedure pulverizes the existing asphalt and blends it with underlying base, subbase, or subgrade materials, which are mixed with cement and compacted to provide a new stabilized base.

This sound engineering and cost-effective technique is popular with state, provincial, county, and city highway agencies attempting to correct their deteriorating pavements and increase the pavements' structural capacity. The FDR with cement technique has been used successfully on pavement projects for more than 25 years resulting in bases that are more uniform, stronger, and provide better long-term performance than the original pavement. Table 1 shows a comparison of flexible pavement rehabilitation strategies.

While the cost advantages of recycling materials from the original pavement are obvious, there are also environmental advantages that are important to the FDR process:

- Conservation of aggregates that must be quarried and transported to the site;
- Conservation of land areas that would be used to dispose of the asphalt and base materials from the failed pavement; and
- Reduced air pollution, traffic congestion, and damage of nearby roadways resulting from hauling new materials to the site, and disposal of old materials.

Since pavements must be maintained over many years, it is important to understand the long-term performance of various pavement construction and rehabilitation procedures. Since the FDR process is roughly 25 years old, the Portland Cement Association (PCA) felt that enough field experience existed to adequately evaluate the long-term performance of FDR with cement. A technical report was completed for PCA that summarized actual field performance of more than 75 projects in eight states scattered across the United States that used the FDR with cement

TABLE 1 Characteristics of Flexible Pavement Rehabilitation Strategies

Solution	Advantages	Disadvantages
Thick structural overlay	Provides new pavement structure; quick construction; only moderate traffic disruption.	Elevation change can present problems for existing curb and gutter and overhead clearances; large quantity of material must be imported; old base–subgrade may still need improvement; high-cost alternative.
Removal and replacement	Provides new pavement structure; failed base and subgrade are eliminated; existing road profile–elevation can be maintained.	Long construction cycle requiring detours and inconvenience to local residents–businesses; increased traffic congestion due to detours, construction traffic; rain or snow can significantly postpone completion; large quantity of material must be imported; old materials must be dumped; highest cost alternative.
Recycling surface, base, and subgrade with cement (FDR)	Provides new pavement structure; fast construction cycle; no detours; minimal change in elevation, thus eliminating problems with curb and gutter, overhead clearances; minimal material transported in or out; conserves resources by recycling existing materials; local traffic returns quickly; rain does not affect construction schedules significantly; provides moisture- and frost-resistant base; least-cost alternative.	May require additional effort to correct subgrade problems; some shrinkage may reflect through bituminous surface.

process (*1*). Results from this extensive investigation into the design, construction, testing, and long-term performance of failed flexible pavements rehabilitated through FDR using portland cement are included in this paper.

SCOPE OF WORK

A list of state and local transportation agencies that were known to have actively used a FDR program was prepared by the investigator in conjunction with PCA. These state, county, city, and private agencies are shown on the project location map in Figure 1. Because the focus of the work was on the long-term performance of FDR with cement pavements, all of the projects studied were at least 3 years old. The average project age was 9 years, and the oldest was 26 years. The age distribution of these projects is shown in Figure 2.

Agency personnel involved with the FDR process were contacted and interviewed about the methodology used to select candidate projects, and about the design and construction of their FDR projects. Performance-related data such as pavement inventory, functional and structural information, traffic data, material composition, amount of cement added, and construction details were collected. Data on pavement subgrades, when available, were collected with the assistance of the highway agencies or experienced FDR contractors.

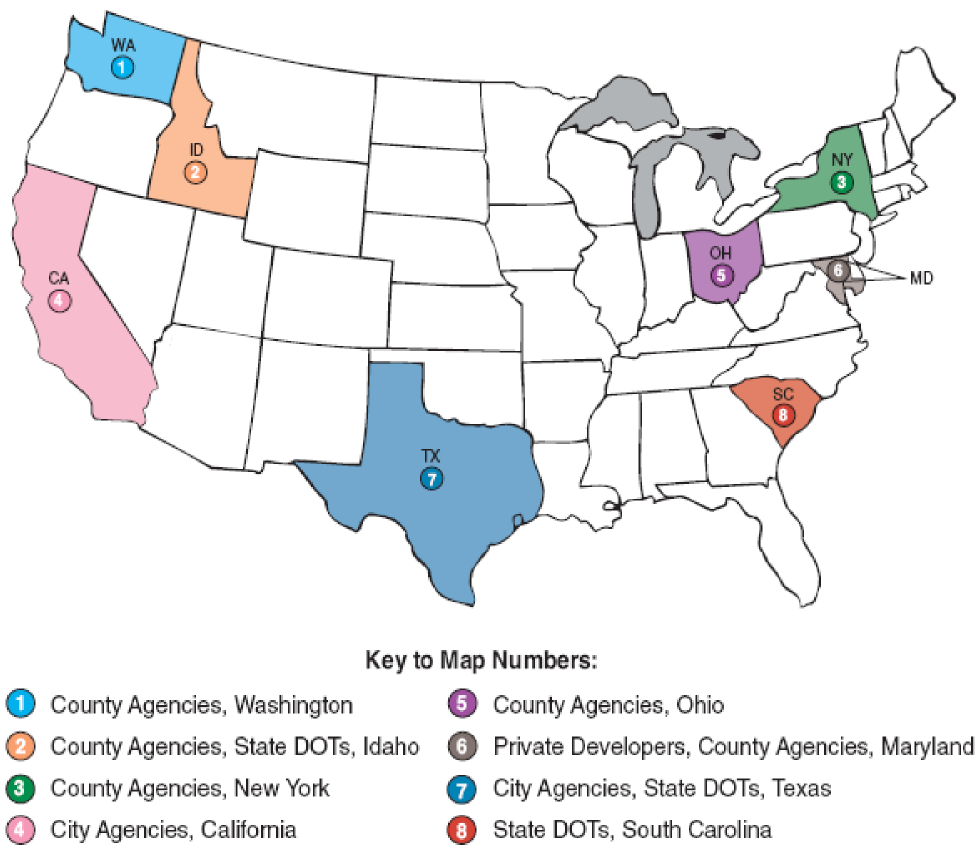

FIGURE 1 Project location map.

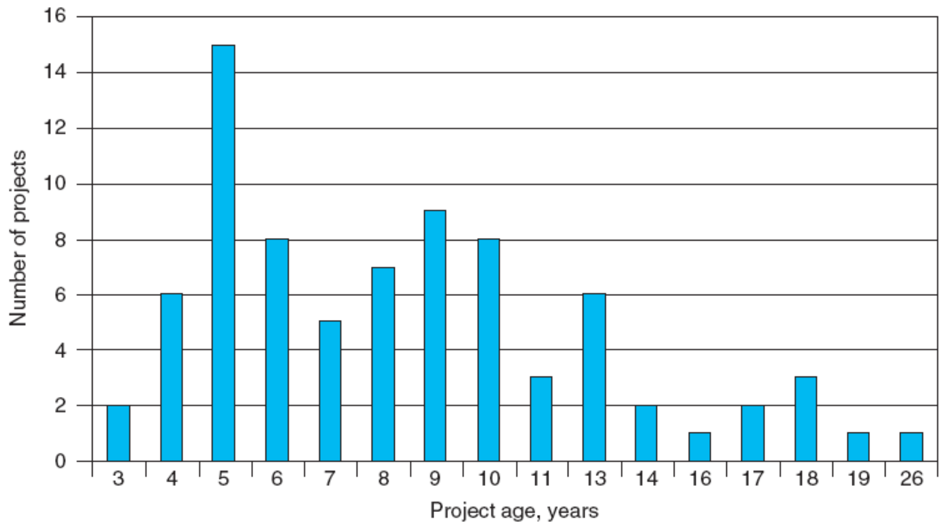

FIGURE 2 Histogram showing age of projects in study.

The extensive performance evaluation process consisted of interviewing the agency–owner of the facility, performing visual pavement surveys, taking cores at select pavement locations, and performing strength measurements on the cores. This provided a qualitative assessment of the long-term strength and stiffness of the reclaimed pavements. Overall, the results showed that the FDR with cement process has had significant success and is extremely popular with public transportation agency engineers and officials, who are trying everything in their power to maintain an acceptable ride quality of their roads in the face of shrinking budgets.

PAVEMENT VISUAL SURVEYS

Pavements rehabilitated using the FDR with cement process underwent a visual inspection, which focused on finding evidence of pavement distress at the selected project sites—particularly distresses that may have been due to the condition of the base (such as block cracking, roughness, and deep potholes). The pavement distresses were systematically recorded to identify their type, extent, and severity. From this data, a numerical composite distress index, termed the pavement condition index (PCI), was calculated. The PCI values range from zero for a failed pavement to 100 for a pavement in perfect condition. Table 2 summarizes the breakdown of PCI values and corresponding pavement surface conditions.

Table 3 summarizes the results of the pavement condition surveys in the study. It shows that almost all of the roads rehabilitated using the FDR with cement process are performing well, with a few exceptions. The overall average PCI for the agencies ranged from 88% to 97% or excellent.

TABLE 2 PCI Value and Pavement Surface Condition

PCI Value	Pavement Condition
0–10	Failed
10–25	Very poor
25–40	Poor
40–55	Fair
55–70	Good
70–85	Very good
85–100	Excellent

TABLE 3 Summary of Pavement Condition Survey

	PCI, %			
Agency	Min	Max	Average	Standard Deviation
City	73	100	89	6
Private developers	95	98	97	2
County	43	100	89	10
State DOT	82	92	88	4
Overall	43	100	89	8

Most of the distresses noted during visual inspection of the pavement sections were in the asphalt layer. Any distresses caused by the base (such as minor reflective cracking) did not affect the roughness or overall road performance. No cases were observed where severe road distress was caused by the reclaimed cement-stabilized base.

LONG-TERM STRENGTH AND DURABILITY

The stabilized base must be strong enough to provide adequate pavement support for the current and future traffic loading conditions. In addition, the stabilized base needs to remain hard and durable and be able to resist the volume changes or hydraulic pressures caused by freezing and thawing and moisture changes that could gradually break down the cementitious bonds.

Representative core samples of the reclaimed base from some of the pavement sections were visually examined and photographed. Upon confirmation of their in situ condition, the cores were subjected to laboratory strength measurements to determine the in situ strength of the reclaimed base after many years of performance. Core samples were obtained from 33 locations, of which 23 were considered adequate for unconfined compressive strength (UCS) measurements as prescribed in ASTM International (ASTM) C42: Standard Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete. The remaining samples were damaged during the coring process. The average UCS was 914 psi (6.3 MPa). Typically, these FDR with cement sections were designed for a 7-day UCS of 400 to 600 psi (2.8 to 4.1 MPa).

In addition to strength, the durability of the road base subjected to wetting–drying and freezing–thawing cycles is a critical parameter for any roadway's satisfactory performance.

Durability issues are especially challenging in wet, northern climates where deeply penetrating freeze–thaw patterns can cause the unstabilized pavement base to lose strength and stiffness. Of the 79 projects that were part of the study, more than 50 sections were in areas with moderate to severe winter weather conditions. Overall, the FDR with cement process has been a very positive experience for agencies in northern areas that have severe weather. The agencies have successfully provided public roads that do not heave in the winters or lose shear strength during spring thaws, and have enhanced road safety. For many agencies, the FDR with cement process has enabled them to build all-weather roads (*2*).

DESIGN

Agency officials realize the importance of design, and do their best in spite of shoestring budgets to perform a proper engineering investigation prior to design and construction of the FDR with cement process. Most of the agencies adopt, to varying degrees, the PCA recommendations in the Guide to Full-Depth Reclamation with Cement (*3*). Some agencies rely on past experience when deciding on the thickness of the reclaimed base and the amount of cement to be added to the mix.

In many cases, little will be known about the materials in the existing pavement and the thickness of the existing layers. The best way to determine these will be to sample the roadway. How frequently the samples should be taken depends on how variable the existing pavement is. The candidate project section is typically sampled at intervals of 0.5 mi (0.8 km). Some engineers add aggregate material if added thickness or modification of materials is required from a pavement design perspective. The thickness of the cement reclaimed base typically ranges from 6 to 12 in. (150 to 300 mm). Depths exceeding 12 in. (300 mm) are difficult to compact in one lift and are not recommended. Selection of the proper base thickness is basically a function of:

- Existing in situ pavement material;
- Thickness required for pavement design;
- Traffic loading; and
- Past experience (in some cases).

FDR pavement thicknesses can be designed using the AASHTO procedure for pavement design or by using thickness design procedures that follow a more mechanistic–empirical process (*4*).

The ability of a pavement base to carry loads depends on the strength of the base material and the depth of the base layer. A thin but strong base can theoretically carry the same load as a thick but weaker base. However, the thin strong base should be avoided because it can become brittle and fracture, resulting in reflection cracks in the pavement surface. When selecting thicknesses for reclaimed pavements, a thicker base with less strength should be preferred. Today's more powerful in-place pulverizing equipment has made the job of obtaining thicker mixed-in-place layers much easier and more reliable compared with equipment used years ago.

Designing the proper amount of water and cement for the stabilized base is not only important to obtain a good final product but it also provides important information for quality control during construction. Publications exist that provide information on testing procedures for determining the appropriate cement content, water content, and compaction requirements for cement-stabilized materials (5). Research has shown that cement-stabilized materials have better strength and performance when they are well compacted, so determining compaction density is fundamental to the design procedure.

The amount of water and cement required in the mix will depend upon the project-specified strength and gradation of the final blend obtained from pulverizing the asphalt during construction and mixing it with the base material. Typical specifications for pulverizing call for 100% passing the 3-in. (75-mm) sieve, a minimum of 95% passing the 2-in. (50-mm) sieve, and a minimum of 55% passing the No. 4 (4.75-mm) sieve. If the blend contains more fine-grained soil, then more cement and water will be required because of the larger surface area of the finer particles.

In most cases, the samples are compacted with varying cement contents using the standard Proctor test outlined in Standard Test Method for Moisture–Density Relations of Soil-Cement Mixtures (ASTM D558). Using the optimum moisture content from the initial moisture–density test, a series of FDR specimens are prepared at different cement contents to determine a 7-day UCS. A target UCS between 300 and 400 psi (2.1 and 2.8 MPa) has been shown to be satisfactory for most FDR applications and is determined by the Standard Test Method for Compressive Strength of Molded Soil-Cement Cylinders (ASTM D1633). Based on an agency's experience, the 7-day UCS design strength varies significantly between 150 and 600 psi (1.0 and 4.1 MPa).

Some agencies in environments subjected to extremes in wet and dry conditions will also perform the Standard Test Methods for Wetting and Drying Compacted Soil–Cement Mixtures (ASTM D559). Additionally, many agencies in the cold climates check the proposed mixture for frost susceptibility by performing a full or partial freeze–thaw test as recommended in Standard Test Methods for Freezing and Thawing Compacted Soil–Cement Mixtures (ASTM D560).

CONSTRUCTION

The construction process for FDR is straightforward. Typical equipment requirements include a pulverizer–mixer (also referred to as a reclaimer), motor grader, cement spreader, water truck, and a roller. The process begins with the reclaimer pulverizing the existing asphalt pavement (Figure 3). Once the existing roadway has been pulverized and blended together, the material is graded to the desired elevation and shape. When working between curb and gutter, there may be a need to remove some of the pulverized material and haul it away in order to leave room for the pavement surface layer.

Type I/II portland cement is usually spread in a controlled manner by spreader trucks that are designed for this operation. Placing the cement in an uncontrolled manner by blowing under pressure should be avoided. Cement is most commonly applied dry (Figure 4), but can also be applied in a slurry form (Figure 5). Most specifications call for the application of cement in terms of weight per area [e.g., pounds of cement per square yard (kilograms of cement per square meter)].

FIGURE 3 Pulverizing a failed asphalt pavement.

FIGURE 4 Placing cement dry.

FIGURE 5 Placing cement in slurry form.

Mixing is performed by the reclaimer–mixer, either by injecting the proper amount of moisture into the mixing chamber (Figure 6), or by placing water on the ground with a water truck in a separate operation. In either case, obtaining the correct amount of moisture is very important in achieving the target compaction. After the materials are well mixed, it is time for compaction and final grading (Figure 7). Smooth-wheeled vibrating rollers or tamping rollers can be used to provide initial compaction, with smooth-wheeled or pneumatic-tire rollers used to complete the operation.

Traditionally, the compaction requirements are 95% to 98% of the laboratory-measured density with the standard Proctor (ASTM D558) energy. Some of the more progressive agencies are now requiring the use of the modified Proctor energy or similar in the laboratory evaluation as described in Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort [56,000 ft-lbf/ft^3 (2,700 kN-m/m^3)], (ASTM D1557). Consequently, these agencies have field density requirements of 95% to 98% of modified Proctor energy.

Proper curing is very important to the quality of the final product. If the base is allowed to dry, it will develop cracks, and the continued gain in strength over time will be compromised. While typical specifications require seven days moist curing, the PCA study found that curing could vary from one-half day to 7 days. For logistical reasons, most if not all the agencies would like to use a shorter curing time. Many agencies do not have alternate detour routes, making it difficult to close the road over an extended period. Some agencies prefer to use moist curing over a period of 3 to 7 days, where others prefer the use of a bituminous coating or a curing compound that can allow the road to be opened to traffic within one-half to 1 day.

FIGURE 6 Water being injected during mixing operation.

FIGURE 7 Compaction and final grading.

The completed FDR base can have any type of pavement surfacing [e.g., chip seal surface treatment, hot-mix asphalt (HMA), or concrete]. The surfacing can be applied as soon as the base is stable (does not rut or shove) under construction traffic. The time required for this can range from 4 to 48 h. Traffic can be placed on the base in the same time frame, as long as repeated applications of heavy trucks are not involved. In many cases with low-volume roads, traffic is allowed to run on the compacted base until the project is ready for surfacing. For conditions where heavy truck traffic is involved, up to 7 days may be required to make sure the base has gained sufficient strength for a high volume of heavy trucks. Field quality control procedures are similar to those used for standard soil–cement base construction (*6*).

INNOVATIVE TECHNIQUES

The major issue with the FDR with cement process is in balancing strength and performance. Figure 8 illustrates how increasing the amount of stabilizer may eventually lead to a decrease in performance (typically because of excessive cracking). The higher cement content yields higher strength, but it increases the stiffness of the reclaimed base, which can become brittle and increase the possibility that cracks in the base may lead to cracks in the asphalt surface. Bases with high cement content will also shrink more, which could also cause reflective cracks. If the engineering design warrants higher strength because of durability issues, then agencies deal with shrinkage cracking challenges by sealing them as they appear.

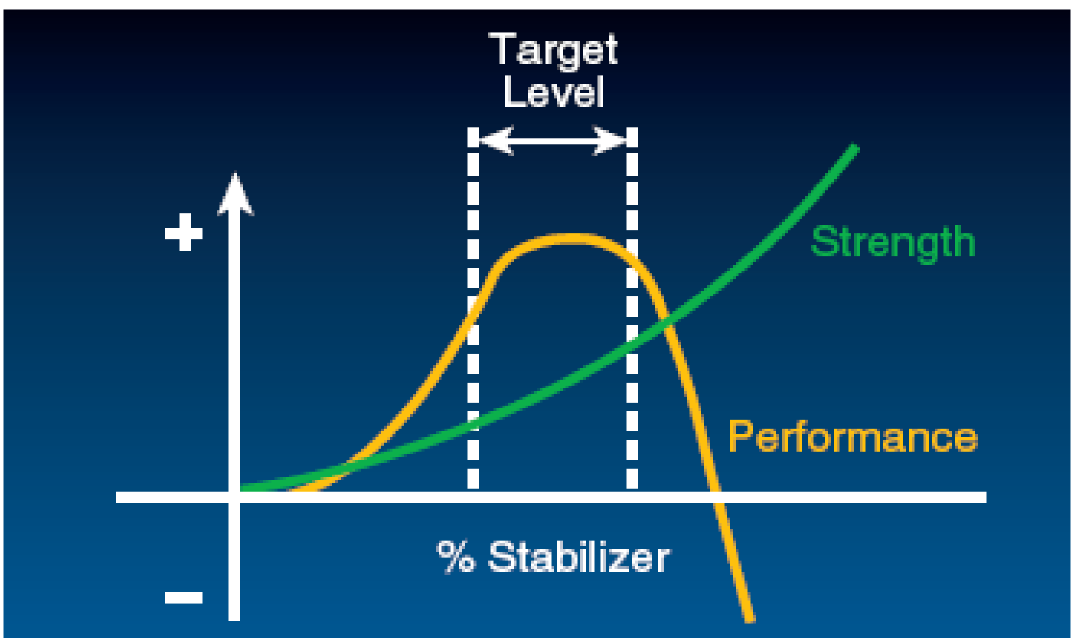

FIGURE 8 Amount of cement becomes a balance between strength and performance.

Agencies realize that durability is the key issue in the design of the FDR with cement mixtures and therefore perform laboratory evaluations to ensure that the FDR with cement mix that they use on their projects is durable. Others try to tweak the UCS test results to get the desired performance. The PCA study showed that the minimum cement content should be based on the mixture passing the durability tests (ASTM D559 or ASTM D560).

Hundreds of thousands of miles (kilometers) of roads with cement-stabilized bases have been constructed in all climates with excellent performance. There are a number of preventative measures that can be taken to minimize the chance that wide cracks will occur in a cement-stabilized material (*7*). Shrinkage cracking is also related to the amount of clayey subgrade soils in the reclaimed layer. Some agencies do not blend subgrade soils in the reclaimed layer. However, because of budget constraints or other design factors, agencies may decide to blend the subgrade soil with the reclaimed materials. They also may use the reclaimed layer to widen their roads from 16 to 20 ft (4.9 to 6.1 m).

Another technique rapidly gaining wide acceptance by agencies is a process called microcracking to reduce reflection cracking. This procedure uses a compaction roller on the surface of the cement-stabilized base 1 to 2 days after construction. The effect of the roller is to initiate hundreds of tiny microcracks in the base to absorb the shrinkage, rather than single shrinkage cracks that are wider. Compared to moist curing alone, microcracking improves the performance of FDR bases by reducing the crack width, reducing the total crack length, or both. Through these mechanisms, microcracking reduces the risk of reflective cracking through the surface layer (*8*).

ECONOMICAL CAPITAL IMPROVEMENT PROJECTS

The FDR with cement process is popular with agencies that seek a cost-effective method to improve their roads. Agencies that use the process save between 30% and 60% over conventional reconstruction methods. Since the FDR with cement process is much quicker, it also saves weeks or months of labor and road closure time. Agencies have been able to blend the underlying poor quality subgrades with the existing pavement and cement to produce a new pavement layer, while at the same time widening the road. The agencies are pleased as they are able to expand their roadways at a fraction of the cost of conventional road construction.

Roads evolve over time as population and demand grows. Consequently, roadway widening over the years introduces nonuniform cross-sections that age or deteriorate at variable rates. The FDR with cement process helps create a uniform section whose long-term performance is more predictable, helping the agency’s pavement management efforts.

Maintenance and rehabilitation activities over the years compromise the crown and cross-slope of the roadway, creating drainage problems. Water ponding within the pavement structure due to inadequate drainage saturates and compromises the subgrade support conditions. The FDR with cement process allows the existing road to be pulverized and bladed to a slope with adequate cross drainage, despite the condition of the original road.

The rehabilitation of urban sections that have curbs and gutters presents a different challenge. How does the engineer increase the strength without increasing the thickness and requiring new curbs and gutters? The FDR with cement process adds strength to the underlying material and allows the removal of some pulverized material, allowing the existing profile to remain without adjustment to cross-slope or curb and gutter elevations.

The FDR with cement process is not a cure for all pavement maintenance and rehabilitation problems, and should not be used in all cases, but its versatility makes it a rehabilitation option to seriously consider for almost every project. The agencies that participated in the PCA study intend to continue the use of the FDR with cement technique and fine tune the process for the future. With over 25 years of experience with the FDR with cement process, the agencies are very satisfied with the long-term performance and are constantly improving techniques for the process.

ENVIRONMENTAL CONSIDERATIONS

FDR with cement conserves virgin construction materials and makes smart economic and strategic sense. A century of modern growth and urbanization in North America has depleted once plentiful aggregate supplies. Frequently, aggregates either come from distant quarries at great expense or from local sources offering only marginal quality.

Continuing to exhaust these valuable resources to rebuild existing roads only propagates and accelerates the problem. Additionally, if old asphalt and base materials are not recycled, they must be disposed of or stockpiled, increasing transportation costs and utilizing valuable landfill space (Figure 9). In some locales, old asphalt can no longer be landfilled. Environmental laws are becoming stricter, thus adding to the expense of mining new materials and landfilling old.

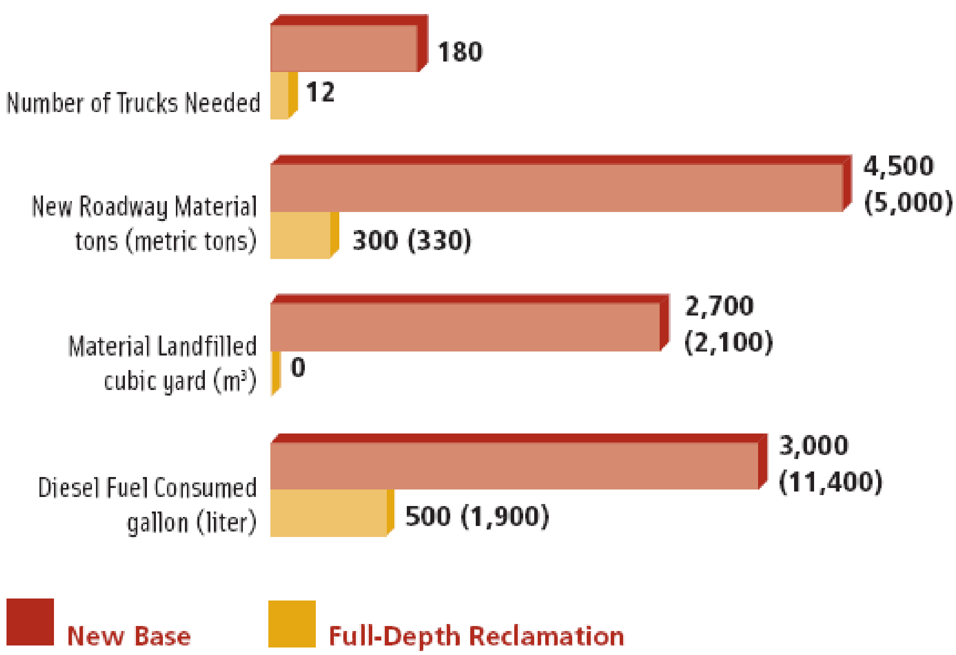

FIGURE 9 Energy use and materials for FDR and new base.

FDR with cement makes the reconstruction of old roads a largely self-sustaining process. The original "investment" in virgin road materials becomes a one-time cost, which is reclaimed through cement stabilization and addition of a new, thin surface course (9). Moreover, some agencies, most notably in California, get state government credit for recycling when they use the FDR with cement process.

SUMMARY

The projects evaluated and summarized in the report prepared for PCA on the long-term durability of FDR with cement pavements included those from six city agencies, three private developers, eight county agencies, and four districts within state departments of transportation. Along with the excellent durability noted in these pavements, one of the biggest advantages of FDR with cement is the versatility that it offers in terms of its use in various geographic and environmental conditions and loading applications.

The PCA study investigated the performance of FDR with cement to rebuild distressed asphalt pavements. The project sections studied were between three and 26 years old with an average age of 9 years. The FDR with cement process is popular with state and local agencies trying to maintain their highway network in the face of shrinking budgets. The economics of the FDR with cement process has helped the highway agencies reconstruct 50% to100% more projects than the conventional construction process.

More than 60% of the projects were in states with severe cold weather conditions and high potential for winter freeze and spring thaw activity. The cement in the FDR process has improved the resistance of the reclaimed base to freeze-related road heaving and thaw-related loss in strength. The highway agencies no longer need to close their roads because of winter freeze or spring thaw. The ability to have their roads open in extreme weather enhances commuter safety and allows businesses to efficiently move goods.

The design process involves an investigation of the existing asphalt pavement structure, followed by a laboratory evaluation of the engineering property of the material and the amount of cement required to produce a durable FDR with cement section. Durability of the FDR with cement section is critical to ensuring acceptable long-term performance. Some agencies perform some version of the durability tests prescribed in ASTM D559 and ASTM D560, while the majority relies on indirect UCS correlations or experience to determine durability of the proposed FDR with cement mix.

Some agencies do not blend subgrade soils in the FDR with cement layer. The performance of the FDR with cement layers minus the subgrade soils is very encouraging, and many agencies are adopting this practice. However, many local agencies are unable to do so because they typically extend the width of their roadways in conjunction with the reclamation process, and don't have adequate pavement structure in place to preclude the use of subgrade soils in their reclaimed layer. The fines content [fraction smaller than sieve size No. 200 (0.075 mm)] of the subgrade soils influences the shrinkage and durability characteristics of the reclaimed mix.

There was no evidence of structural failure in the FDR with cement sections. More often, the distress on the pavement surface was in the HMA-overlay. Reducing the cement content to eliminate shrinkage cracks needs to be balanced with durability requirements. The minimum cement content required for a durable FDR with cement mix should be the only criterion. If that mix exhibits shrinkage cracks, then those cracks need to be sealed, or reduced through microcracking.

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PAVEMENT PERFORMANCE AND PRESERVATION PROGRAMS

Concrete Pavement Preservation and Rehabilitation to Meet Sustainability Demands

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Roadway agencies with flat or reduced budgets need to implement cost-effective, engineered strategies to preserve and rehabilitate the country's aging and deteriorating pavements so that the pavements can carry increased traffic volumes and vehicles loads. In addition, agencies need to improve the sustainability of their pavement systems—reduce pavements' environmental footprint while increasing their contributions to the country's economic and social well being. Research is validating the value of concrete as a durable, sustainable material for concrete construction, maintenance, and rehabilitation solutions. Agencies have a large toolbox of concrete-based maintenance and rehabilitation solutions for both concrete and asphalt pavements, and research and technology transfer activities are helping agencies implement these tools more effectively and sustainably. To implement concrete pavement solutions effectively and sustainably, agencies need to adjust their mindset to a more proactive approach. This paper discusses the meaning of sustainability in regard to pavements. It encourages agencies to invest more time and effort in critical, up-front planning in advance of implementing pavement maintenance and rehabilitation solutions. The paper includes suggestions for conducting thorough pavement condition evaluation and solution selection processes, incorporating environmental, economic, and social sustainability considerations.

The need has never been greater for cost-effective, engineered strategies to preserve and rehabilitate pavements. The nation's roadway system is aging—some original concrete sections of Interstate highways are still in service after 30, 40, and even 50 years—and these aging pavements are deteriorating. According to the Bureau of Transportation Statistics, one-third of the country's pavement system, about 1.3 million miles, is in poor condition or worse. Traffic volumes and vehicle loads on this aging system continue to increase, while roadway budgets continue to fall short of needs. As a result, street and road agencies must implement pavement maintenance and repair solutions that not only restore but enhance pavements' structural and functional characteristics and that, at the same time, are more cost-effective.

Street and road agencies face yet another 21st-century challenge: enhance pavements' sustainability. A basic definition of sustainability is the capacity to maintain a process or state of being into perpetuity. In the context of human activity, sustainability has been described as activity or development "that meets the needs of the present without compromising the ability of future generations to meet their own needs" (*1*). In the context of pavement systems and for purposes of this paper, sustainable pavements are those that, from design through rehabilitation, use environmentally friendly materials and practices and enhance the public's economic well being and general quality of life.

Altogether, these sobering realities require street and road agencies to implement no less than a new generation of sustainable pavement solutions.

SUSTAINABLE PAVEMENT

Research is confirming that concrete has many characteristics that make it a sustainable material for pavements. One research track of the National Concrete Pavement Research Road Map (*2*) is focusing on concrete pavement sustainability. The National Road Map is a long-term research plan developed and now implemented by a collaborative effort of the FHWA, state highway agencies, and industry. The Road Map's Sustainability Track emphasizes and coordinates environmental-focused efforts in the 12 other tracks, so that sustainability is an integrated emphasis, from pavement design through mix design and proportioning through equipment advancements through construction. Projects in other priority tracks in the National Road Map—one track focusing on concrete pavement surface characteristics and one focusing on business and economic practices—are enhancing the economic and social benefits of concrete pavements.

Although efforts to improve concrete sustainability are ongoing, street and highway agencies already have access to a variety of sustainable, concrete-based pavement maintenance and repair solutions. What is needed is not necessarily new technologies or solutions, but a new, proactive mindset toward using them. By focusing more time and effort on upfront evaluation and planning activities, agencies can optimize existing technologies and solutions, preserving the equity in pavements and enhancing their functional and structural capacity, all for less than the cost of reconstruction.

This paper describes this proactive approach. Specifically, it focuses on tools to help agencies thoroughly evaluate existing pavement conditions and, based on those conditions, select optimum concrete solutions. Effective use of these evaluation and selection tools can make the new generation of sustainable concrete pavement solutions a reality today (Figure 1).

Much of the information in this paper is based on three resources recently developed by the National Concrete Pavement Technology Center (National CP Tech Center) at Iowa State University, in conjunction with FHWA:

- The Concrete Pavement Preservation Manual (*3*) describes the correct implementation of preventive pavement maintenance and preservation strategies, as well as a systematic approach to evaluating pavement conditions and selecting optimum strategies.
- The Guide to Concrete Overlays: Sustainable Solutions for Resurfacing and Rehabilitating Existing Pavements (*4*) includes details about evaluating the conditions of an existing pavement to determine if it is a good candidate for a concrete overlay, and a flowchart for selecting an appropriate overlay solution.
- The Integrated Materials and Construction Practices for Concrete Pavement: A State-of-the-Practice Manual (*5*) can help roadway agencies and contractors enhance concrete

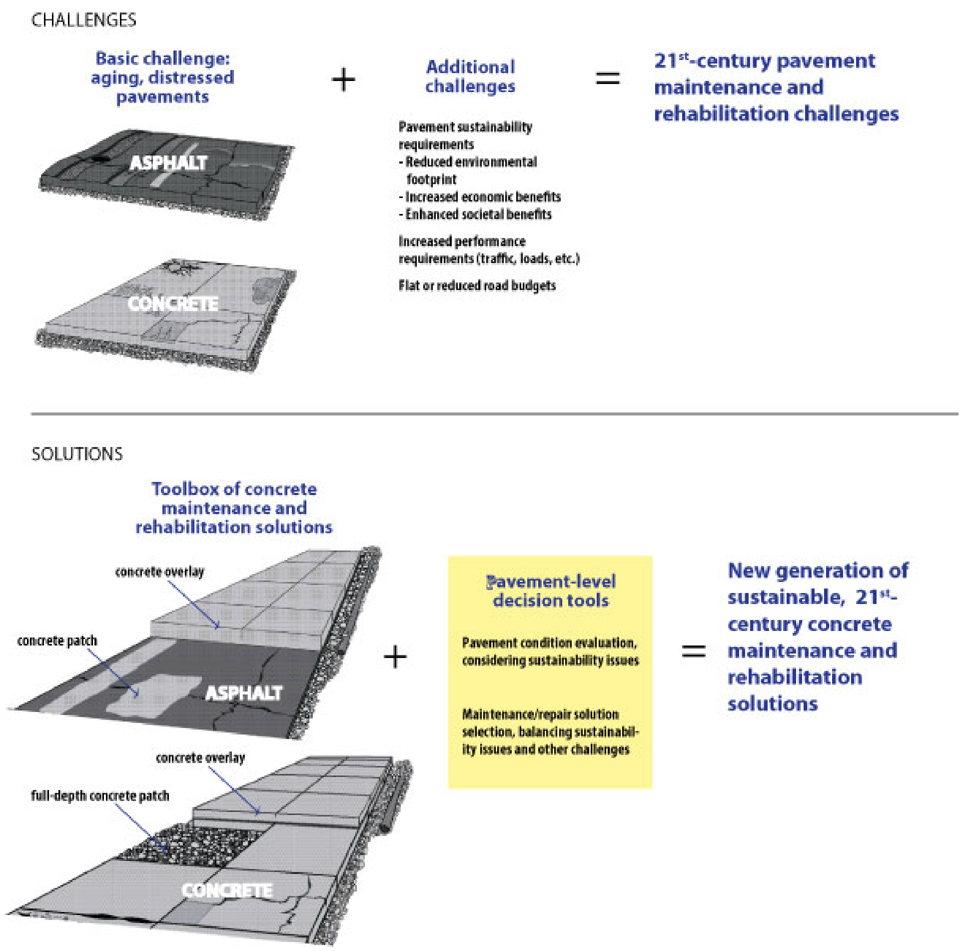

FIGURE 1 Implementing a new generation of pavement solutions requires spending more time on pavement-level condition evaluation and solution selection.

pavement sustainability by implementing state-of-the-art pavement design, materials selection and mixture proportioning, and construction quality-control practices.

What Does Sustainable Pavement Look Like?

The concept of pavement sustainability can be illustrated by a three-legged stool, as in Figure 2. Just as a stool is level and sturdy when its three legs are balanced, pavement is sustainable when its three areas of impact—environmental, economic, and social—are equally considered and balanced. The stool will topple if any leg is missing or shorter than the others. Likewise, pavement is not sustainable if the environmental, economic, and social impacts of materials and practices used in pavement design, construction, operation, maintenance, restoration, rehabilitation, and recycling are not equally considered and carefully balanced.

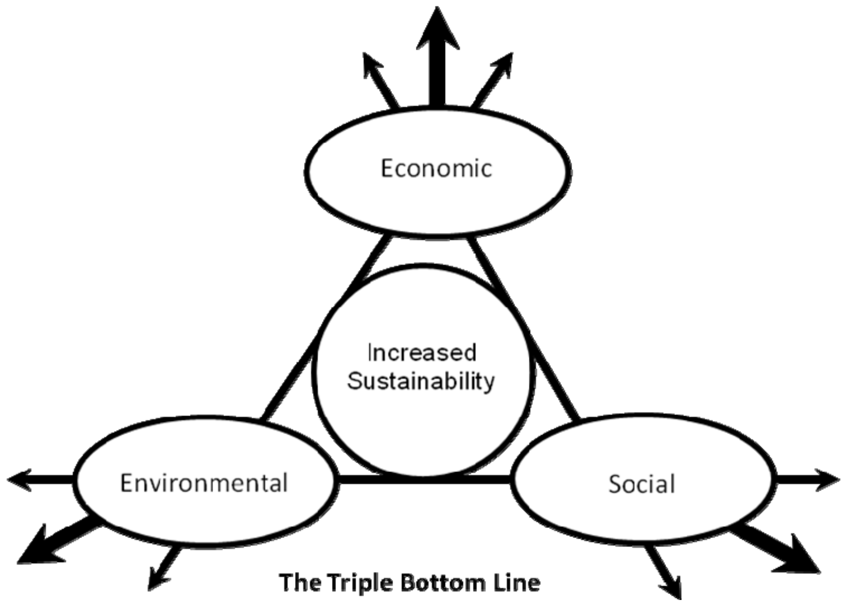

FIGURE 2 Pavement sustainability requires balancing the "triple-bottom line" impacts of pavements—environmental, economic, and social.

Sustainable pavements strike a balance between minimizing their environmental footprint and maximizing their economic and social benefits. Agencies currently lack the measuring tools and historical data to fully quantify and compare pavements' environmental, economic, and social impacts—that is, to balance the triple bottom line of pavement sustainability. A priority of the Sustainability Track of the National Concrete Pavement Research Road Map (*2*), therefore, is to develop such tools and collect such data.

As a material for new pavement construction and for pavement maintenance and rehabilitation, many agencies are recognizing, and research is validating and improving, concrete's sustainability characteristics such as the following:

- Concrete pavements can be rehabilitated by preserving and enhancing the existing structural capacity of the existing pavement, for less than the cost of reconstruction.
- Concrete solutions such as concrete overlays that retain the existing pavement in the solution can provide structural improvements and preserve the remaining equity in deteriorating pavements for several decades.
- Concrete pavement's durability and long life can increase life-cycle benefit-to-cost ratio.
- Concrete pavement's durability and long life can reduce frequency and duration of work zones, resulting in fewer schedule disruptions due to traffic delays, fewer delay-related vehicle emissions and fuel consumption, and less maintenance-related intrusion into surrounding ecosystem.
- Concrete pavement's durability and long life can reduce fuel consumption and emissions for materials production and transportation, pavement placement, and maintenance activities.

- Concrete pavement mixtures can incorporate industrial byproducts, reducing waste burdens on landfills.
- Concrete pavement's light surface color can increase surface reflectivity, resulting in improved nighttime visibility, reduced energy needed to power nighttime illumination, and mitigation of both urban heat islands and smog generation.
- Existing concrete pavements can provide the support system for a new surface layer.
- Concrete can be 100% recycled as, for example, lower-quality aggregate in the lower lift of a two-lift pavement system or as the base layer for a reconstructed pavement.
- Concrete pavement surface textures can be optimized, using new surface characteristics guidelines, to reduce tire-pavement noise over the short and long term and to reduce splash–spray during wet conditions (*6*).
- Concrete pavements have minimal deflection under load, which can reduce vehicle drag and related fuel consumption.
- Pervious concrete pavement shoulders, parking lots, and driveways can reduce storm water runoff and help replenish aquifers.

In addition to concrete's potentially sustainable characteristics as a material for pavements, many elements of a new, sustainable generation of concrete pavement maintenance and rehabilitation solutions exist.

- Pavement management systems are helping agencies account for their pavement investments.
- Agencies have a well-stocked toolbox of cost-effective, engineered, concrete pavement maintenance and rehabilitation solutions.
- New tools are available to help agencies evaluate the conditions of specific pavements and understand the short- and long-term implications of those conditions.
- New tools are available to help agencies select optimum concrete pavement maintenance and rehabilitation treatments and timing for delaying, or even preventing, the need for more expensive, intrusive solutions.

These elements are available, but successfully implementing them into a successful program for sustainable pavements requires nothing less than a new way of thinking about and approaching pavement maintenance: keep pavements young.

Agencies can keep pavements young by proactively expending more planning time and effort up front. The proactive efforts should include thoroughly evaluating existing pavement conditions and then—based on pavement distresses, future loading and traffic volume requirements, and budget and sustainability considerations—selecting optimum solutions and schedule their implementation at the optimum time. Finally, the solutions must be well designed and constructed for the specific pavement conditions and needs.

Pavement Management Systems

In 1991, to promote a long-term, proactive approach to decision making regarding funding for pavement maintenance and construction activities, the Intermodal Surface Transportation Efficiency Act of 1991 required state agencies to develop pavement management systems. This requirement was dropped in later legislation, but today most state and many local road agencies are using pavement management programs to cost-effectively manage and account for their network-level pavement investments. Through these programs, agencies regularly collect and monitor network-level pavement history and condition information, then use data analysis and decision-making software to optimize schedules for maintenance or other work across the network. The scheduling algorithms in pavement management systems are based on the concept that pavement preservation activities provide the greatest benefit-to-cost ratio.

Pavement Preservation

Pavement preservation is defined as "a program employing a network-level, long-term strategy that enhances pavement performance by using an integrated, cost-effective set of practices that extends pavement life, improves safety, and meets motorist expectations" (*7*). In general pavement preservation activities restore or extend the functional or structural condition of existing pavements in good condition and delay costly major rehabilitation or reconstruction.

A pavement preservation program keeps good pavements in good condition through a strategic, network-wide program of routine maintenance, preventive maintenance, and minor rehabilitation activities, as shown in Figure 3.

Routine Maintenance

Routine maintenance activities focus on maintaining or preserving pavement at a satisfactory level of service. Routine maintenance activities include joint and crack re-sealing.

Preventive Maintenance

Preventive maintenance is a planned strategy of cost-effective treatments to a pavement structure to preserve the system's condition, retard its future deterioration, and maintain or improve its functional condition, without significantly increasing its structural capacity. Preventive maintenance activities may extend the service life of structurally sound pavements and reduce, control, or correct minor problems. Examples include partial and full-depth repairs, retrofitted edge drains, load transfer restoration, diamond grinding and grooving, and slab stabilization.

Minor Rehabilitation

Minor rehabilitation strategies restore some structural capacity to a pavement. Doing so may also restore surface functionality, extend service life, and address nonstructural problems. Examples include bonded and thin unbonded concrete overlays.

The window for effectively accomplishing preservation activities for various pavement conditions is shown in Figure 4.

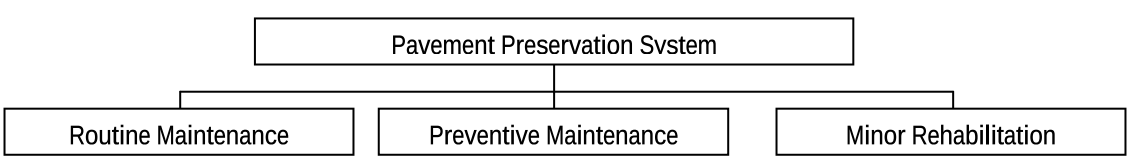

FIGURE 3 Pavement preservation consists of three types of activities.

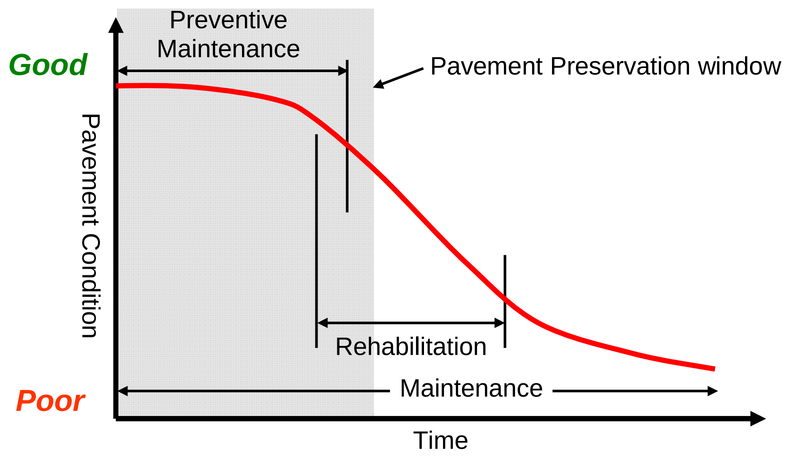

FIGURE 4 Relative timing of preventive maintenance and rehabilitation techniques (*3*).

Major Rehabilitation

When pavements need structural repair or improvement, major rehabilitation is the typical solution. Rehabilitation involves making structural enhancements that extend the service life of an existing pavement and improve its load-carrying capability. Examples include some types of unbonded concrete overlays.

Major rehabilitation is generally more expensive and invasive than pavement preservation activities. Therefore, a major goal of pavement preservation is to prevent or delay the need for major rehabilitation as long as possible. Still, compared to total reconstruction, carefully selected major rehabilitation strategies that meet specific pavement needs can cost effectively keep pavements young longer.

Evaluating Pavement Conditions

Pavement management programs (PMPs) focus on network-level big picture pavement condition evaluation and treatment decision-making. In addition to a PMP, a proactive approach to keeping pavements young requires an additional, more comprehensive condition evaluation of a specific pavement or pavement segment before a treatment can be selected and implemented. Conducting a detailed evaluation takes extra planning time and effort but is critical to help an agency understand a pavement's distresses and other conditions, its performance capabilities and limitations, and the implications of various potential treatments.

A thorough pavement condition evaluation provides valuable information such as the following:

- Presence, type, and extent of distress;
- Structural condition and load-carrying capacity;
- Functional characteristics of the pavement, such as roughness, friction, and noise;
- Characteristics and behavior of in-place pavement materials; and
- Sustainability issues.

Several activities can be performed as part of the evaluation process and will vary from project to project, depending on the project type and relative significance. Generally, the process can be divided into the following steps, summarized in Figure 5:

- Historical data collection, records review, and future needs projections;
- Visual surface examination;
- Core analysis;
- Possible additional tests, including analyses of material-related distresses, drainage, roughness and surface friction, and grade restrictions; and
- Condition assessment profile, summarized in condition assessment evaluation–sustainability report.

Evaluation Step 1: Historical Data and Future Projections

The first step is to collect data from office files and other historical records associated with the project. The goal is to collect as much information about the existing pavement as possible, such as original design data, construction information, subgrade–subbase data, materials testing data, traffic data, performance data, and so on. Possible data sources for this effort include the following:

- Design reports,
- Construction plans–specifications (new and rehabilitation),
- Materials and soils properties from previous laboratory test programs or published reports,
- Past pavement condition surveys, nondestructive testing or destructive sampling investigations,
- Maintenance–repair histories,
- Traffic measurements–forecasts, and
- Environmental–climate studies.

The information gathered in this step can be used to divide the pavement into discrete sections with similar design and performance characteristics.

This step includes determining future performance requirements, like expected traffic loadings and overlay design life.

Evaluation Step 2: Visual Examination

The second step is a visual site inspection to gain initial information about the pavement's condition. At a minimum, information should be gathered on pavement distress, road roughness, surface friction, shoulder conditions, and moisture–drainage problems, as well as traffic control constraints, obstructions, right-of-way zones, presence of bridges and other structures, and general safety issues. Discussions with local design and maintenance engineers may be beneficial.

Pavement distress in the form of visible defects or deterioration of the pavement is the most basic indication of an existing pavement's current performance and structural condition. To evaluate pavement condition more completely, the type, severity, and extent of distresses should be examined in detail.

- Types of distress are determined primarily by occurrence and appearance and can indicate the underlying causes of deterioration.
- Severity of distress represents the criticality of the distress in terms of progression; more severe distresses will require more extreme rehabilitation measures.
- The extent of each distress type and severity level must be measured.

Information obtained in this step will be used to determine the type and extent of additional field testing that may be required, such as roughness measurements, falling weight deflectometer (FWD) testing, or coring and materials testing.

A review of the existing profile grade line should be conducted; areas of significant deviation will have to be investigated through analysis of core samples. Evidence of numerous active panel movements in a concrete or composite pavement may indicate potentially unstable or nonuniform subgrade support or material-related distress. These, too, will require detailed pavement analyses to determine the extent of distress and possible corrective actions. For example, if movement is confined to isolated areas, full-depth repairs in these areas may be considered.

Localized panel tenting (early stages of blowups) may indicate the build-up of compressive forces in the slabs and may exhibit voids or loss of support beneath slab corners. Sections with significant tenting can be repaired to relieve the pressure and provide uniform support.

Evaluation Step 3: Pavement Coring (As Needed)

The third step is to take cores from the existing pavement. The cores help owners determine layer thickness and identify the pavement’s support value, the kind and condition of layer materials, depth of distress, and, if the existing pavement is composite, the condition of the existing bond between layers. Cores that penetrate into the subgrade may show evidence of unstable conditions, such as the beginning of fine soil migration into open-graded subbase layers that can lead to plugging and instability. Cores also provide samples for possible laboratory analyses.

Evaluation Step 4: Optional Analyses

Various factors affect the necessity for and extent of additional pavement evaluation tests. These factors include the existing pavement condition and performance as determined during the first three steps of the evaluation process: roadway classification, current and future traffic volumes, especially truck traffic, current and future service life, and budgetary constraints. Additional analyses may not be required for lower road classifications, such as local streets. Possible optional analyses include the following.

Laboratory Testing Lab tests may be conducted to confirm or clarify results from the visual examination, reveal distress mechanisms, and provide additional information needed to identify feasible treatments. Examples of information determined from lab tests include the following:

- Concrete strength data,
- Stiffness of existing concrete and asphalt and of composite layers,
- Petrographic testing and analysis of material-related or other durability distress,
- Condition and support provided by the subgrade and subbase,
- Concrete permeability,
- Asphalt stripping, and
- Coefficient of thermal expansion of concrete.

Material-Related Distress (MRD) A detailed engineering evaluation of the type, degree, and state of MRD (such as D-cracking or alkali–silica reaction) may be warranted.

Deflection Testing Pavement deflection testing is an effective way to assess a pavement's structural capabilities. Pavement deflection tests are not required for all pavements, especially those in fair-to-good condition or perhaps those on lower-volume roads.

Subgrade Strength Testing When signs of subbase–subgrade problems exist a determination of the California bearing ratio or *k*-value or modulus of subgrade reaction can be determined through deflection testing or through dynamic cone penetrometer testing.

Drainage Surveys Unless moisture-related problems are identified and corrected, the effectiveness of any maintenance strategies will be reduced. The purposes of a drainage survey are to

- Detect and identify moisture-related distress,
- Document prevailing drainage conditions (e.g., cross slopes, cut–fill areas, depth and condition of ditches), and .
- Assess edge drain conditions, if present.

Possible drainage problems indicated by a drainage survey may suggest the need for in-depth analysis of the pavement structure's drainability. DRIP (Drainage Requirements In Pavements), an FHWA computer program, can assist in such an analysis (*8*).

Roughness and Surface Friction Tests Roughness and surface friction are two key indicators of the functional performance of a pavement, providing information on the rideability and safety of the pavement.

Onboard Sound Intensity Consideration should be given to tire–pavement noise issues.

Elevations and Grade Restrictions Consideration should be given to the effects of potential maintenance activities on grade change, particularly at bridge underpasses and approaches, at-grade intersections, shoulder areas, and curb and gutter units.

Table 1 presents a summary of the different pavement characteristics included in an evaluation, and the different testing methods used to assess them.

TABLE 1 Areas of Overall Condition Assessment and Corresponding Data Sources (*3*)

Attribute	Distress Survey	Drainage Survey	Deflection Testing	Roughness Testing	Friction Testing	Field Sampling and Testing
Structural adequacy	✓	✓	✓			✓
Functional adequacy	✓			✓	✓	
Drainage aAdequacy	✓	✓	✓			✓
Materials durability	✓	✓	✓			✓
Maintenance applications	✓					
Shoulders adequacy	✓		✓			✓
Variability along project	✓	✓	✓			✓

Evaluation Step 5: Sustainability Issues

At this juncture in pavement evaluation, sustainability issues related to the specific pavement or pavement segment should be thoroughly considered. For example, can anything be done to mitigate a pavement's contribution to storm water runoff? Or is splash and spray during rain events a problem that could be mitigated with a specific surface treatment?

Evaluation Step 6: Condition Assessment Profile and Evaluation–Sustainability Report

When all aspects of an existing pavement have been evaluated, the critical distresses and drainage conditions should be summarized. One useful way to summarize this information is to plot it on a condition assessment profile, or strip chart (*2*). In bar chart form, this profile visually indicates where various distresses occur over the length of the project, as well as their extent and severity.

Results of data collection and analyses, as well as potential sustainability issues not directly related to pavement distresses, should be summarized in an evaluation report. Any critical nonpavement factors, such as shoulder condition, ditches, right-of-way, curves, bridges, ramps, and traffic patterns should be identified in the report. Ultimately, this information will be used in the identification and selection of appropriate treatment strategies.

Toolbox of Solutions

For the broad range of pavement conditions, an abundant toolbox of cost-effective, engineered concrete solutions exists. Examples include proven technologies and practices such as partial and full-depth repairs, as well as new or improved strategies, like concrete overlays. Following is a brief overview of a few common solutions:

- Joint resealing,
- Partial-depth repairs,

- Full-depth repairs,
- Load transfer restoration,
- Diamond grinding, and
- Concrete overlays, bonded and unbonded.

Joint Resealing

Joint and crack sealing serves two primary purposes. It reduces moisture infiltration into a pavement structure, thereby reducing moisture-related distresses such as pumping, joint faulting, base and subbase erosion, and corner breaks. It also prevents the intrusion of incompressible materials, thereby reducing or preventing pressure-related distresses such as spalling, blowups, buckling, and slab shattering. Problems like these, over time, can cause serious damage and necessitate major rehabilitation.

Partial-Depth Repairs

Partial-depth repairs restore a pavement's structural integrity and improve its ride quality. They can also restore a well-defined, uniform joint sealant reservoir prior to joint resealing. Partial-depth repairs are appropriate for repairing surface distress or deterioration that is limited to the top one-third of the slab.

Full-Depth Repairs

Full-depth repairs restore ride and structural integrity where concrete pavements exhibit various types of structural distresses, including transverse cracking, corner breaks, longitudinal cracking, deteriorated joints, blowups, and punchouts. Where severe spalls are present along a transverse joint, a full-depth repair of the joint may be more cost effective than a series of individual partial-depth repairs. Full-depth repairs are often used to prepare distressed concrete pavement sections before a structural concrete overlay is constructed.

Properly timed, designed, and constructed full-depth repairs can restore a pavement to "like new" condition. They are more expensive than partial-depth repairs but are critical for reducing or preventing continued deterioration of the distressed area or, if an overlay is placed, preventing premature failure of the overlay. At the same time, highways with low traffic volumes may not require repair at the severity level recommended for highways with higher traffic volumes.

Load Transfer Restoration

Load transfer restoration (LTR) is the installation of dowel bars at transverse joints or cracks to provide positive load transfer of wheel loads across slabs and reduce deflections. The devices are retrofitted in existing pavements that do not have load transfer devices or in which the existing devices are not working. The procedure can also provide positive load transfer across random transverse cracks. Restoration of load transfer can enhance pavement performance by reducing pumping, faulting, and corner breaks, and also by retarding the deterioration of transverse cracks. Diamond grinding of the pavement surface is often done in conjunction with LTR to restore ride.

Diamond Grinding

Diamond grinding is a surface restoration procedure that corrects concrete pavement surface distresses or deficiencies. Diamond grinding can be an effective, long-term treatment for restoring or improving pavement smoothness and reducing tire-pavement noise while producing ample macrotexture for good skid resistance. It may be conducted alone as a pavement preservation strategy or as part of a series of pavement preservation treatments such as full-depth repair and LTR.

Concrete Overlays

Although concrete overlays have been constructed for decades, their use is now increasing as agencies are learning more about their potential applications and correct design and construction procedures. Concrete overlays can be useful tools not only for correcting existing pavement distresses but also for cost effectively enhancing a pavement's overall sustainability.

There are two types of concrete overlays, bonded and unbonded. Either can be constructed on existing concrete, asphalt, or composite pavements.

Concrete overlays preserve and extend pavement service life. Many concrete overlays have been in service for decades, extending the life of the original pavement structure for 20 years or more. As long as the original pavement remains stable and uniform, a concrete overlay can be placed, replaced, or recycled for many decades. The owner continues to maintain and build equity in the pavement system and realize a return on the original pavement investment.

Agencies that regularly construct concrete overlays describe several benefits.

- They are cost-effective long-term maintenance and rehabilitation options, in and of themselves or in conjunction with a few spot repairs of isolated distresses.
- The existing pavement does not have to be removed. In fact, it is factored into the overlay design.
- They can be constructed quickly, using accelerated construction practices throughout the normal construction season.
- Depending on the requirements, some concrete overlays can be opened to traffic within a day of placement.
- Concrete overlays are easy to repair. A distressed panel needs to be removed only if ride quality is a problem. Thin overlays without reinforcement can be easily and economically milled out and replaced with a new concrete surface.
- Concrete overlays provide cost-effective solutions for almost any pavement type and condition, desired service life, and anticipated traffic loading.
- Concrete overlays improve surface reflectance (albedo), increase structural longevity, and enhance surface profile stability.

Bonded Concrete Overlays

Bonded concrete overlays are relatively thin [2 to 5 in. (50 to 125 mm)] and, together with the existing pavement, produce one monolithic pavement. Bonded concrete overlays are generally constructed to add structural capacity to and eliminate surface distresses on existing pavements that are in good to fair structural condition. Bonded overlays provide resurfacing solutions for routine or preventive pavement maintenance or for minor rehabilitation.

Factors that affect the performance of the resurfaced pavement include the strength and integrity of the underlying pavement, the effectiveness of the bond between the existing pavement and the overlay, the ability of the two layers to move monolithically to maintain the bond, and overlay jointing and curing techniques. Therefore, using materials and construction practices to achieve and maintain a strong bond is particularly important. In a bonded concrete overlay on a concrete pavement, for example, the coefficient of thermal expansion (CTE) of aggregate in the overlay should be similar to or less than that of the existing concrete pavement to prevent differential expansion between the two layers that could prevent or break the bond.

Unbonded Concrete Overlays

Unbonded concrete overlays are typically thicker overlays [4 to 11 in. (100 to 275 mm) on concrete and composite pavements; 6 in. (150 mm) or more on asphalt pavements less than 6 in. (150 mm) thick after milling]. An unbonded overlay performs essentially like a new pavement, and the existing pavement provides a stable base.

Unbonded overlays are generally constructed to restore structural capacity to existing pavements that are moderately to significantly deteriorated. Unbonded overlays are minor or major rehabilitation strategies.

With unbonded overlays on asphalt or composite pavements, partial or full bonding between the concrete overlay and the underlying asphalt layer may occur and should not cause a problem. If the underlying pavement is concrete, however, unbonded concrete overlays must be carefully designed and constructed to separate and prevent bonding between the two concrete layers.

The key to good performance of unbonded concrete overlays is that major structural defects be identified and repaired prior to overlay construction to provide a uniform base.

Selecting the Optimum Concrete Solution

A thorough pavement evaluation report is the primary basis for selecting optimum pavement solutions. To some extent, certain solutions are best suited to specific pavement distresses, as listed in Table 2.

In many situations, however, agencies are well served by expending additional time and effort up front to carefully evaluate, compare, and then select the most appropriate, sustainable solutions. As described in both the Concrete Pavement Preservation Manual (*3*) and the second edition Guide to Concrete Overlays (*4*), several steps are involved in the treatment selection process.

Selection Step 1: Identify Potential Treatments

In general, the following assessments can be used to help identify those treatments that may be appropriate for a given project:

- Assess slab support conditions. When assessing the support conditions of concrete slabs, it is important to test for voids at slab corners, as well as test the load transfer efficiency at transverse joints. One good indication that there is a slab support problem is the presence of pumping (i.e., the presence of fine material on the pavement surface at the transverse joints). Concrete slabs that currently do not have structural problems (e.g., corner breaks or linear cracking), but are found to have voids or poor load transfer are good candidates for slab stabilization or load transfer restoration.

- Correct localized distress that is contained in the upper one-third of the slab. In concrete pavements, it is not uncommon to have localized areas of distress that are contained in the upper one-third of the slab thickness. At joints, common distresses in this category include joint spalling, or map cracking, crazing, or scaling. If any of these distresses are present in an amount or severity that requires attention, a partial-depth repair is typically the best treatment to correct the distress.
- Correct localized distress not contained to the upper one-third of the slab. When a pavement evaluation locates distress that is not contained to the upper one-third of the slab (e.g., corner breaks, transverse cracking, or material-related distress), a full-depth repair is typically required to correct the observed distress.

TABLE 2 Preventive and Rehabilitation Treatment Options (*3*)

	Treatment Options									
	Preventive								**Rehabilitation**	
Distress	Slab stabilization	Partial-depth repair	Full-depth repair	Retrofitted edge drains	Load transfer restoration	Diamond grinding	Grooving	Joint resealing	Bonded concrete overlay	Unbonded concrete overlay
Corner breaks			✓							✓
Linear cracking			✓							✓
Punchouts			✓							✓
D-cracking			✓							✓
Alkali–aggregate reaction			✓							✓
Map cracking, crazing, scaling		✓								
Joint seal damage								✓		
Joint spalling		✓	✓							✓
Blowup			✓							✓
Pumping	✓			✓	✓					
Faulting					✓	✓			✓	✓
Bumps, settlements, heaves			✓			✓			✓	✓
Polishing						✓	✓		✓	

- Correct functional distresses. Many otherwise sound concrete pavements may be exhibiting functional deficiencies, such as poor friction or excessive roughness. Diamond grinding is typically used to correct roughness problems, but it also has a positive impact on a pavement's friction characteristics. If the only functional problem is found to be a localized area of poor friction (such as at curves or intersections), diamond grooving is often an effective treatment option.
- Assess joint sealant condition. In general, if the original concrete pavement was sealed at the time of initial construction, then every effort should be made to maintain an effectively sealed joint over the life of the pavement. Therefore, if there are any signs of joint sealant damage, or if any other treatment alternatives have caused the effectiveness of the joint sealant to be compromised, joint resealing should be considered. When conducted with other treatments, joint resealing should always be the final activity performed on a pavement before it is opened to traffic.

Selection Step 2: Identify Key Selection Factors and Constraints

It is important to check the list of potential treatments against a list of other key selection factors or any project-specific constraints that may come into play. These may include factors such as following:

- Sustainability issues, such as potential environmental and user impacts of work zones, materials availability, traffic congestion issues, potential traffic engineering improvements for better traffic flow, etc.;
- Environmental impact;
- Conservation of natural resources;
- Available funding;
- Future maintenance requirements;
- Geometric restrictions;
- Lane closure time;
- Agency's experience with the use of the treatment;
- Traffic safety during construction;
- Worker safety during construction;
- Contractors' experience with the treatment;
- Availability of needed equipment and materials;
- Competition amount providers of materials;
- Stimulation of local industry;
- Agency policies; and
- Political concerns.

On any specific project, many of these factors may not be an issue when selecting treatments. However, it is important that all outside constraining factors, including sustainability, be identified at this point of the selection process to avoid conducting unnecessary work or missing opportunities.

The new factor on this list is sustainability issues. All factors need to be considered in light of how they help enhance environmental, economic, and social benefits of sustainable pavements. For example, a potential treatment strategy for a seriously deteriorated pavement might be to repair all distresses as appropriate with partial- or full-depth patches, retrofitted edge drains, load restoration, diamond grinding, and other solutions. Another treatment strategy may be to repair only structural distresses, then place an unbonded overlay. The initially less-expensive strategy may provide fewer opportunities to or be less effective at enhancing sustainability by

- Using recycled materials in the project;
- Minimizing equipment fuel consumption and emissions;
- Minimizing frequency and duration of work zone disruptions for the public;
- Extending the service life of the existing pavement; and
- Optimizing surface characteristics for smooth ride and adequate friction and reflectivity.

Although research is being planned to develop measurement tools and collect data regarding various pavement sustainability factors, it is reasonable and likely that maximizing pavement sustainability will, in the long term, provide a higher benefit–cost ratio. From this perspective, adding sustainability factors to the selection process means including the value of sustainability factors in life-cycle cost analyses. See Step 4, below.

Selection Step 3: Develop Feasible Treatment Strategies

A treatment strategy is a plan that defines what treatments to apply and when to apply them, over a selected time period. For example, a strategy using only one treatment could be to conduct diamond grinding every 8 to 10 years for the next 25 years. Another strategy could be to conduct dowel bar retrofitting activities, followed by diamond grinding during the same construction project. It is not uncommon to concurrently conduct more than one of the concrete pavement preservation activities in a single project, because various concrete pavement preservation activities complement each other. Therefore, the purpose of this step is to

- Determine all activities needed to best address the pavement's needs; and
- Determine if the activities should be conducted as part of one project or at different times.

Each individual treatment combination or treatment timing scenario can be considered a separate treatment strategy for the pavement.

Selection Step 4: Assess Life-Cycle Costs

While there is usually an obvious choice for the most appropriate strategy, competing strategies can be objectively compared by considering the overall the life-cycle cost associated with each.

Life-cycle cost analyses can be useful to determine if and when the strategic application of pavement preservation activities, individually or together with other preservation treatments like overlays, should be seriously considered because they will result in significantly delaying the need for more expensive rehabilitation activities. For example, diamond grinding a faulted pavement (assuming an ongoing structural problem is not contributing to the faulting) that is otherwise in good structural condition will slow pavement deterioration (by reducing dynamic loading effects) while providing a smoother, safer traveling surface.

In general, however, the presence of the following distresses at critical levels or severities may indicate that the window for pavement preservation has closed, and major rehabilitation strategies are required:

- Blow-ups,
- Corner breaks,
- Severely deteriorated cracks,
- Materials-related distress, and
- Punchouts (continuously reinforced concrete pavements).

As mentioned in Step 3, life-cycle cost analyses can be especially useful when they cost-out sustainability benefits of various activities. [Note: agencies currently lack tools for measuring various economic and societal benefits related to sustainability. A priority of the Sustainability Track of the National Concrete Pavement Research Road Map (2) is to develop such tools. In the meantime, assigning values to such benefits in a life-cycle cost analysis can be subjective and arbitrary.] Examples of such benefits include the following:

- Reducing costs associated with long and/or frequent work zones (traffic delay costs, vehicle operating costs, etc.);
- Reducing freight damage due to a rough road;
- Implementing a more durable, long-lasting treatment;
- Increasing traffic safety and reducing crash costs; and
- Improving traffic flow and/or reducing congestion.

Selection Step 5: Select Preferred Strategy

In some cases, specific project constraints or selection factors (Step 3) may override life-cycle costs. Ultimately, the goal is to select the alternatives that best addresses current pavement conditions; present and future functional, structural, and sustainable requirements; and short- and long-term budget issues.

It is not uncommon for different treatments to be applied in a single project. However, these activities should follow a logical construction order that protects and maximizes the effectiveness of each.

Forever-young pavements = sustainable pavements

Keeping pavements young with the new, sustainable generation of concrete pavement solutions requires agencies and contractors to change their approach to street and road maintenance and rehabilitation programs. Sustainable pavements result when agencies take full advantage of pavement management systems and their toolbox of pavement treatments, and when they proactively and accurately evaluate specific pavement conditions and select and implement optimum concrete pavement solutions. Sustainable pavements last longer, extend the return on original pavement investments, deplete fewer raw materials and help consume waste materials, reduce fuel consumption and emissions, facilitate motorists' safe and uninterrupted trips, and reduce overall life-cycle costs.

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Implementation of a Pavement Preservation Program in Illinois

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The implementation of pavement preservation programs is a growing trend among transportation agencies in the United States. During the 2005 fiscal year, the State of Illinois began the process of implementing a pavement preservation program by providing appropriated funding for specific pavement preservation treatments for state-maintained roadways. Since that time, the program has expanded the funding level for the same four treatments on state-maintained roadways. In addition to providing funding, the State of Illinois has supported the creation of state- and local-level guidelines that are planned to become part of both the Bureau of Design and Environment Manual and the Bureau of Local Roads and Streets Manual, respectively. Further resources were provided to conduct pavement preservation training throughout the state. The implementation of a pavement preservation program has been a learning experience for the state. This paper highlights the challenges and successes of the state's implementation. It includes a discussion of the role of industry in supporting the program, the creation of pavement preservation guidelines to provide information regarding the importance of preservation and guide the selection of treatments for both state- and local-level roadways, and the development and delivery of customized pavement preservation training throughout the state. It concludes with a discussion of the challenges that Illinois Department of Transportation faces moving forward with their program.

Over the past several years, the Illinois Department of Transportation (IDOT) has evaluated the need to incorporate pavement preservation activities into its policies and procedures. The first projects using the appropriated funds were let on the July 31, 2004, letting and used rough guidelines to determine treatment selection. After the first round of projects, the guidelines were revised to address issues encountered during the first projects. The current guidelines were finalized on March 7, 2005, and issued in a joint memorandum between IDOT's Bureau of Design and Environment (BDE) and Bureau of Materials and Physical Research (BMPR) in September 2005. That memorandum (BDE PM 47-05/BMPR PM 05-06) provided guidelines for selecting proper preservation treatments for appropriate state system projects; however, it did not provide specific treatment selection criteria and did not address preservation policy needs for local roads and streets. Therefore, the IDOT BMPR and the Bureau of Local Roads and Streets (BLRS) together initiated a study in 2007 to develop pavement preservation guidelines for both the state roadway system and the local agency roads and streets in Illinois.

The development of guidelines was initiated to support IDOT's pavement preservation program at the state and local level. The pavement preservation program started by IDOT is unique in several ways. Specifically, industry spearheaded the effort for the initial pavement preservation program and the BMPR and BLRS worked jointly to improve pavement preservation practices by developing project and treatment selection guidelines. Furthermore, a statewide training initiative was undertaken to introduce the program and improve pavement preservation knowledge.

This paper summarizes Illinois' pavement preservation program from both the state and local agency level. It begins with a general introduction to pavement preservation practices, provides details of the unique aspects of IDOT's program, and addresses the challenges the agency faces in moving forward with the program.

PAVEMENT PRESERVATION

Many transportation agencies, including IDOT, are using pavement preservation programs to more cost effectively manage their pavement assets. As a means of improving the functional condition of the network and reducing the overall rate of deterioration of the pavement asset, preventive maintenance treatments are a key component of a pavement preservation program. Since they are relatively inexpensive in comparison to resurfacing or reconstruction projects, preventive maintenance treatments are an effective means to preserve the investment in the pavement asset. An effective pavement preservation program has two main objectives:

1. Preserve the pavement investment. This objective involves minimizing the structural failures and extending the structural life of the pavement to preserve the investment the agency has made in the pavement asset.
2. Maintain a high level of service (LOS). This objective involves maintaining acceptable smoothness and surface friction in order to provide a high LOS for the roadway customers.

The implementation of a pavement preservation program is good practice, as it focuses on maximizing the condition and life of a network of pavements while minimizing the network's life-cycle cost. With a common goal of creating a preservation program, industry and IDOT worked together to promote preservation practices in the state for both state-maintained and local agency roadways.

ROLE OF INDUSTRY IN THE PRESERVATION PROGRAM DEVELOPMENT

The evolution of pavement preservation within the State of Illinois would not have been possible without the contributions of industry, and specifically the efforts of the Illinois Pavement Preservation and Maintenance Association (ILPPMA). The ILPPMA is a group of contractors specializing in providing pavement preservation treatments such as microsurfacing, slurry seals, chip seals, and cape seals. The group supported legislation to provide appropriated funding for specific pavement preservation treatments for state-maintained roadways.

On their website, the ILPPMA states their goal is to place the right treatment on the right road at the right time. They also have the following specific objectives:

- Educate users on the quality, safety features, and effective uses of preventive maintenance practices.

- Continue to refine and develop quality specifications for preventative maintenance treatments.
- Promote pavement preservation concepts and products in the State of Illinois.
- Work to continue to increase funding for pavement preservation in the State of Illinois.
- Remain a recognized representative for preventive maintenance in the State of Illinois.

It was through their efforts and initiatives that pavement preservation has been moved closer to the forefront for maintaining IDOT's road network.

CREATION OF PAVEMENT PRESERVATION GUIDELINES

Although initial funding had been secured, IDOT and industry recognized the need for quality preservation guidelines and specifications. Therefore, the BMPR and the BLRS at IDOT supported the development of pavement preservation policies for flexible and rigid pavements for state- and local-maintained roads.

In order to follow the development of IDOT's pavement preservation guidelines, it is necessary to understand the history of pavement preservation within IDOT. IDOT is composed of various offices and divisions, as shown in Figure 1. The development of pavement preservation policies and guidelines was focused within the Division of Highways, specifically for the BLRS and the BMPR. Both bureaus are involved in program implementation for the Division of Highways, as shown in Figure 2. The details of the guidelines developed for both bureaus are provided in the following sections.

Local Agency Pavement Preservation Guidelines

The BLRS provides guidance and assistance to local agencies. Specifically, guidance is provided in the areas of planning, financing, designing, constructing, and maintaining local highway and street systems. These activities are further supported by the policy development and technology transfer activities conducted by the BLRS. Hence, the BLRS policy and technology engineer supported the development of pavement preservation guidelines for local agencies to provide a consistent process of treatment selection for all agencies so that federal funds can be used to finance preservation treatments.

Local agencies in Illinois have a history of using pavement preservation treatments, so they are familiar with many pavement preservation treatment options and have created internal documents to improve the success of various treatments. For example, Terry Fountain, the Local Roads and Streets Engineer for District 6, developed a handbook on the subject entitled Seal Coats (Oil and Chipping). This manual serves as a resource for agencies and is used as the basis for a training course targeted at local agencies wanting to improve their seal coat operations.

Although these types of resources exist for some local agencies, there was still a need for detailed preservation guidelines to expand the list of preservation treatment options. The

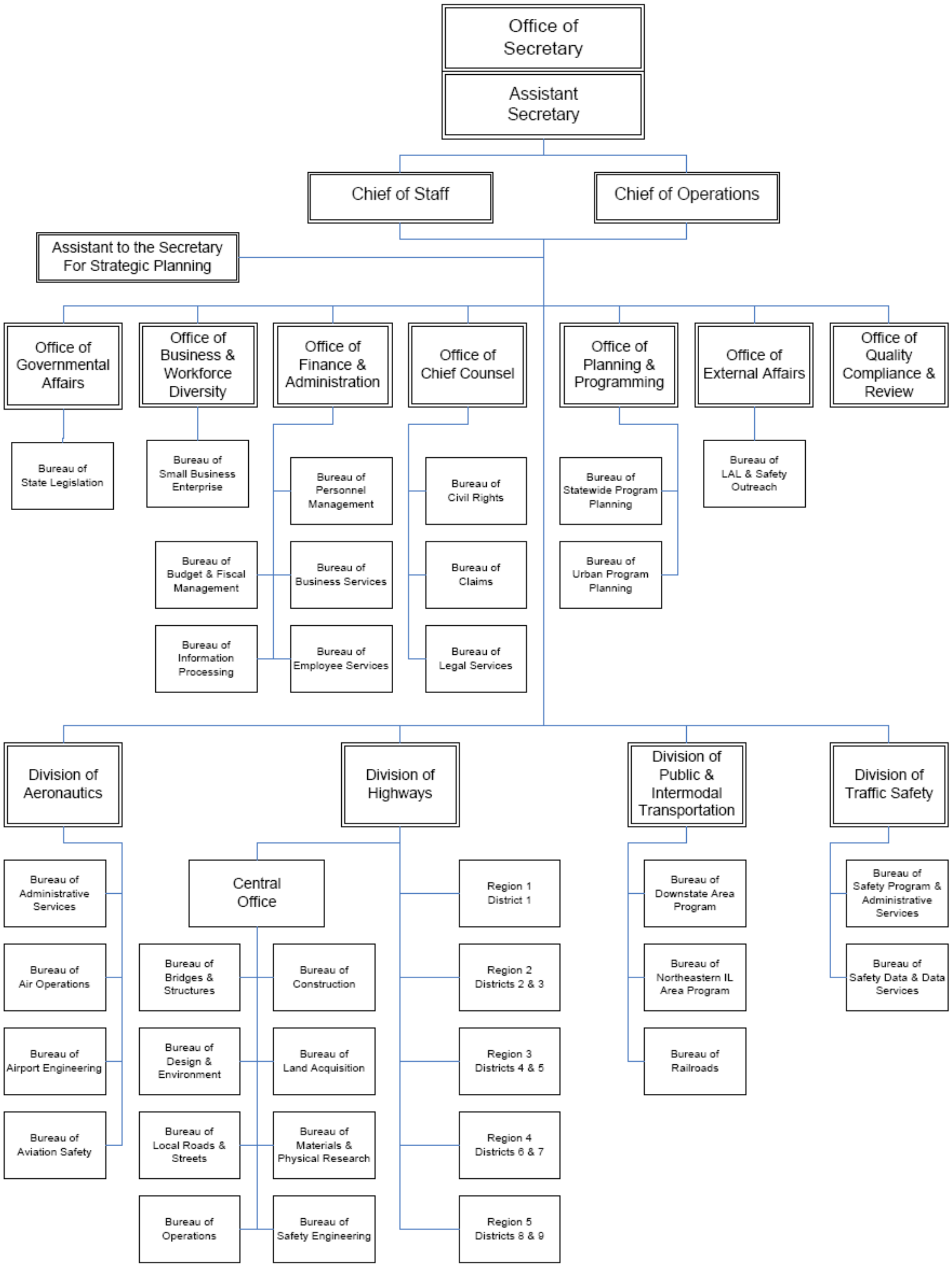

FIGURE 1 Organizational chart for IDOT.

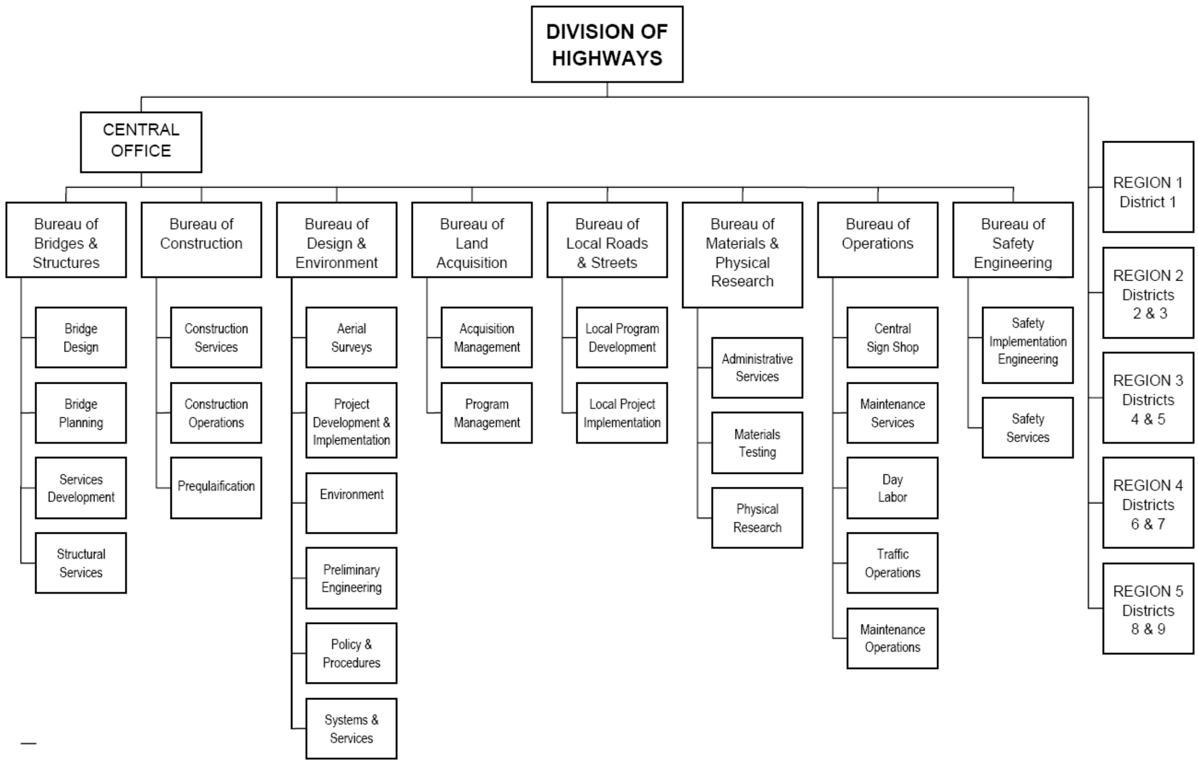

FIGURE 2 Organizational chart for the Division of Highways within IDOT.

guidelines developed for the local agencies included a process for program approval, a detailed summary of available pavement preservation and minor rehabilitation treatments, and guidelines for treatment selection as described in the following sections.

Process for Program Approval

The first portion of the BLRS preservation guidelines outline the procedures needed to allow agencies to conduct pavement preservation with all sources of funding including motor fuel tax, state funds, or federal funds. In order to track the performance of the pavement sections over time and to support pavement preservation funding requests submitted to the District BLRS office, local agencies are requested to develop a pavement management system (PMS). The PMS can take the form of proprietary software, nonproprietary software, or a simple spreadsheet.

The preservation guidelines suggest that pavement condition surveys should be conducted at least every 3 years on all roadways included in the pavement preservation program. Ideally, all roadways maintained by the agency, not just those included in the pavement preservation program, will be included in the survey so the pavement conditions can be tracked over time and the data can be used when making treatment selections as additional sections are added to the pavement preservation program.

The three basic steps of the local agency pavement preservation process are described below:

1. Program approval. Agencies interested in participating in the pavement preservation program must submit a participation form to the BLRS for review.
2. Preservation plan development. The agency will develop a 10-year pavement preservation plan and submit it to BLRS for review. The first section, explaining the first 2 years of the 10-year plan, should detail specific pavement preservation projects proposed for funding. The remaining section, explaining the final 8 years of the plan, should include a summary of the proposed total miles of preservation projects that are planned in each year. Because preservation projects are based upon selecting the right treatment at the right time, it is difficult to schedule long-range preservation projects. Therefore, it is more appropriate to note the number of miles proposed for each type of treatment during the remaining 8 years of the pavement preservation plan.

   Upon approval by the BLRS, necessary funding will be allocated for use on the preservation treatments.
3. Pavement preservation plan updates. Each year, the agency should update the list of projects included in the first 2 years of the pavement preservation project plan. On even-numbered years, the number of miles of pavement preservation projects planned for the last 8 years of the 10-year plan should be updated. An estimate of pavement preservation program cost should be submitted to the BLRS for review.

This process was developed to provide a standard means of outlining the use of federal funds for pavement preservation activities.

Summary of Pavement Preservation Treatments

In addition to outlining the general pavement preservation process for local agencies, the BLRS also needed to provide information regarding the types of treatments that a local agency can use to support their pavement preservation efforts. Many different pavement preservation techniques and minor rehabilitation treatments are available for flexible and rigid pavements as described in the guidelines. The treatments shown in Table 1 range from localized applications to treatments applied to the entire pavement surface. For all preservation treatments, the purpose is to minimize the effects of pavement distress or prevent them from occurring.

Within the guidelines, one-page summaries of each treatment are provided. They outline treatment description, pavement conditions addressed, application limitations, construction considerations, traffic considerations, special considerations, expected performance period, and relative cost for each treatment. Each treatment summary is followed by a simple pictorial representation of the major steps of the construction sequence. The information provided introduces local agencies to the variety of preservation treatments available to them.

Pavement Preservation Treatment Selection

For the identified treatment types, the guidelines then outline the pavement preservation treatment selection process. Appropriate maintenance strategies are determined based upon the current condition of the pavement and the types of distresses present. In some cases, a combination of preservation strategies is needed to correct the combination of distresses present on the pavement. The process of selecting the most appropriate combination of pavements and treatments for preservation activities includes the following general steps:

TABLE 1 Pavement Preservation Treatments Available for Local Agency Use

Treatments for Flexible Pavements	Treatments for Rigid Pavements
Crack filling	Crack sealing
Crack sealing	Joint resealing
Fog seals	Diamond grinding
Sand seals	Diamond grooving
Scrub seals	Full-depth repairs
Rejuvenators	Partial-depth repairs
Slurry seals	Load transfer restoration
Microsurfacing	Cross stitching
Chip seals	Pavement subsealing–undersealing
Cape seals	
Cold in-place recycling	
Hot in-place recycling	
Ultrathin bonded wearing course	
Ultrathin whitetopping	
Cold milling	
Drainage preservation	

- Gather pavement information;
- Assess pavement condition;
- Evaluate pavement data;
- Identify feasible preservation treatments; and
- Select most appropriate preservation treatment.

Gather Pavement Information

Selecting appropriate preservation techniques includes the collection of historical pavement information. The type of information needed to select the right projects and treatments include (*a*) pavement type, (*b*) pavement age and design life, (*c*) traffic, and (*d*) pavement cross section and materials. This type of information can exist in a PMS and accessed to make an informed selection of the right treatment at the right time on the right road.

Assess Pavement Condition

In addition to gathering historical pavement information, the current condition of the pavement must be assessed in order to determine feasible preservation treatments. Ideally, the condition would be determined through a standard condition rating procedure, including details of the types, severities, and amounts of distresses present on the pavement. Local agencies can utilize a variety of condition rating procedures to assess the condition of the pavement.

Evaluate Pavement Data

In order to determine whether a pavement section is a good candidate for pavement preservation treatments, the agency should consider the following:

- Is there excessive distress (large quantities or severe levels of distress) on the pavement section or are the occurring distresses a warning sign of an underlying structural problem?
- Is there other evidence of structural problems?
- Has the time for applying a pavement preservation treatment to the pavement while it is in good condition passed?
- Are there other known pavement problems (e.g., material problems or signs of construction problems) on the pavement section?
- Is there a history of pavement problems in this location?

If the answer to the majority of these questions is no, then the pavement section is likely a good candidate for pavement preservation techniques. For pavement sections for which the answer to most of these questions is yes, the agency should not consider preservation techniques and instead plan major rehabilitation or future reconstruction for the roadway.

Identify Feasible Preservation Treatments

One input for determining the appropriate treatment strategy for those pavement sections identified as candidates for pavement preservation is the type and severity of pavement distresses present on the pavement. Guidelines for determining recommended and feasible treatments are provided based upon related attributes such as distress levels, ride, friction, traffic levels, and relative cost. These guidelines are primarily based on a relationship between a single treatment and a single distress. When multiple distresses exist, the appropriate treatment to address each distress type should be examined and recommended treatments must be selected using engineering judgment.

Select Most Appropriate Preservation Treatment

Of the feasible preservation treatments, the most appropriate treatment is one that can provide the best benefit-to-cost ratio while meeting the constraints of the project. There are several methods to identify the treatment with the most benefit for the associated cost. This analysis is done internally with many PMS. Ideally, the selection of the right treatment at the right time is governed by optimization (maximizing benefits for given constraints). However, treatment selection can be accomplished through a manual assessment of the benefits compared to the estimated project cost.

In addition to the benefits and costs of the feasible treatments, the selection of the most appropriate preservation treatment includes consideration of the variety of project constraints that affect treatment selection. The types of project constraints that should be considered when selecting the most appropriate preservation treatment include:

- Availability of qualified contractors;

- Availability of quality materials;
- Agency practice or local preference;
- Time of year of construction;
- Initial costs;
- User preferences;
- Pavement noise;
- Facility downtime; and
- Surface friction.

The effects of these constraints vary from project to project and should be considered as the final projects are selected for inclusion in the local agency's pavement preservation program.

State-Level Pavement Preservation Guidelines

The BMPR also supported the development of pavement preservation guidelines, but from a different perspective than the BLRS. The BMPR is comprised of three main sections: test section, physical research section, and administrative services section. Together, these sections are involved in a number of studies including materials; new product evaluations; and special pavement management, design, and rehabilitation activities. The development of pavement preservation guidelines for the BMPR provides State engineers with guidance to select from predefined treatments that are allowed for use with the appropriated funds.

At the state level during the past 20 years, IDOT has focused on the use of HMA overlays to maintain the surface condition of the roadways. The recent shift to using pavement preservation as a potential pavement treatment has been a change for agency personnel. Specifically, IDOT began a pavement preservation program for state-maintained roadways during fiscal year (FY) 2005. Building on the support from industry, the program focuses on four treatments using specifically earmarked funds: bituminous surface treatment (BST), slurry seal, microsurfacing, and cape seal. In the first year of the program, nearly $3 million were allocated for use in the state, with approximately $300,000 spent in each of the nine districts in the state.

Initially, Half-SMART (Surface Maintenance at the Right Time) treatments, consisting of the placement of a 0.75-in. leveling binder and a single-pass BST, were eligible for pavement preservation funding. However, by FY2006 only the BST portion of the Half-SMART overlay could be funded with the pavement preservation program funding. Other treatments, such as thin hot-mix asphalt (HMA) overlays, crack sealing, and patching, are not allowed for use with the appropriated funding, so they are not an official part of the IDOT pavement preservation program for the state-maintained roadways.

As of January 2008, a total of 60 projects covering approximately 460 lanemiles of roadway and costing approximately $9.3 million had been completed on state-maintained roadways. Over the 2008 construction season more projects were added; the total number of pavement preservation projects funded in Illinois since the start of the pavement preservation program in FY2005 is detailed in Table 2. Also in spring 2008, pavement preservation funding was increased to $7 million per year, with approximately $800,000 required to be spent by each of the nine districts on the allowable treatments.

BMPR developed further guidance on the use of treatments eligible for pavement preservation funding (BST, slurry seal, microsurfacing, and cape seal). The guidance is developed in terms of special provisions that provide details of new technology, equipment, and materials related to the specific treatments. The state-level guidelines are still being finalized, but were initially developed to include general pavement performance information, a detailed summary of available pavement preservation and minor rehabilitation treatments, and guidelines for treatment selection as described in the following sections.

Pavement Performance

Understanding how pavements perform and deteriorate over time is one of the keys to an effective pavement preservation program. Therefore, a section regarding pavement performance is included in the guidelines. This section highlights the causes of pavement deterioration for various types of pavements so the information can be used to apply pavement preservation techniques at the optimal time.

Summary of Pavement Preservation Treatments

Although pavement preservation funding at the State-level is only allowed for the construction of BSTs, slurry seals, microsurfacings, and cape seals, the development of the state-level pavement preservation guidelines are planned to include details of the majority of the treatments included in the local agency guidelines (Table 1). A final decision of what treatments to include in the guidelines will be made when they are incorporated into the next revisions of the Bureau of Design and Environment Manual, which is planned to be effective in January 2010.

Pavement Preservation Treatment Selection

The general pavement preservation treatment selection process developed was similar for both the local agency and state-level guidelines. The process of selecting the most appropriate combination of pavements and treatments for preservation activities includes the following general steps, which are identical to those incorporated into the local agency guidelines:

- Gather pavement information;
- Assess pavement condition;
- Evaluate pavement data;
- Identify feasible preservation treatments; and
- Select most appropriate preservation treatment.

TABLE 2 Summary of Pavement Preservation Projects in Illinois Since FY2005

Treatment Type	Number of Projects Completed
Bituminous surface treatments (1-pass BST)	6
Single-pass slurry seal	5
Single-pass microsurfacing	15
Two-pass microsurfacing	23
Cape seal(1-pass BST and 1-pass microsurfacing)	14
Half-SMART overlay (leveling binder and 1-pass BST)	8

The main difference in the process is that, at the state level, IDOT's standard condition rating survey process is used to assess pavement condition as compared to the variety of rating procedures that can be used by the local agencies.

DEVELOPMENT AND DELIVERY OF CUSTOMIZED PAVEMENT PRESERVATION TRAINING

In addition to developing both the state- and local-level guidelines for pavement preservation, IDOT supported the development and delivery of a customized 1.5-day pavement preservation training course to all nine Districts. Training was targeted at state-level IDOT employees involved in planning, design, and construction of pavement preservation treatments, although classroom spots were also filled by various local agencies wanting to learn more about preservation treatments.

The pavement preservation training focused on crack sealing, BSTs, slurry seals, microsurfacings, and cape seals. The training was based on the National Highway Institute course materials and IDOT special provisions for these treatments, developed and maintained by the BMPR.

The training course content, customization issues, and development and delivery schedule were finalized in a meeting between IDOT and the teaching consultants. Based upon input from the meeting, the consultants customized the course materials (including a participant workbook and presentation slides) to address IDOT policies, procedures, and specifications. The training course provided the opportunity to further discuss IDOT's pavement preservation program and to expand the pavement preservation treatment knowledge of state DOT and local agency employees.

CHALLENGES OF IMPLEMENTING PAVEMENT PRESERVATION PROGRAM

As Illinois moves forward implementing pavement preservation they are going to face a variety of challenges at both the local and state levels.

Local-Level Implementation Challenges

In order to ensure the success of pavement preservation on the local highway system in Illinois, the BLRS has established an implementation plan that relies on education, training, and technical assistance. The implementation plan relies heavily on the Illinois Local Technical Assistance Program (IL LTAP) and its location within the BLRS Local Policy and Technology Unit. This unique relationship allows technology transfer to be based on existing and planned policy decisions. BLRS has implemented a pilot program to capture local issues and revise the program accordingly. The following four challenges are currently being addressed:

1. Confusion with definitions–terminology;
2. Lack of PMS;
3. Procurement using federal funds; and
4. Statewide specifications.

Confusion with Definitions–Terminology

In the early 1990s, BLRS issued a policy titled Local Agency Pavement Preservation (LAPP). The LAPP policy allowed local highway agencies to use federal funds to perform a small amount of pavement patching or correct crown issues. The LAPP policy also required a thin HMA overlay that would provide an 8-year minimum service life. Because of the title of this policy, pavement preservation is misunderstood by some agencies within Illinois.

The IL LTAP Center published several articles dealing with pavement preservation in the quarterly Illinois Interchange newsletter. These articles highlight the importance of selecting the right treatment and not limiting options. The IL LTAP has also held annual rehabilitation, preservation, and maintenance seminars across the state. These seminars highlight effective treatments, but also differentiate between treatments selected through a comprehensive preventive maintenance program and those selected as reactive maintenance–rehabilitation.

Before being approved to participate in the pilot pavement preservation program, BLRS meets with the local agency and IDOT District Office to explain the purpose of pavement preservation. This meeting also provides feedback on what additional information or training locals may need to successfully implement the program.

Lack of PMS

The Illinois highway system is comprised of more than 140,000 mi of roads, and IDOT has jurisdiction over more than 16,000 mi of the total system. The remaining 124,000+ miles are under the jurisdiction of counties, municipalities, and road districts. More than 99,000 mi are considered rural and the remaining 41,000+ miles are considered urban. IDOT uses the Illinois Roadway Information System (IRIS) as a statewide roadway inventory for the roads for which it has responsibility.

While IRIS has detailed information, including condition ratings, on most of the 16,000 mi of state highway, data fields on the local system are often missing or incomplete. Furthermore, even if IRIS contained pavement condition information concerning local highways, IRIS was not developed as a PMS. Therefore, detailed forecasting and program alternative comparisons are not a part of IRIS.

Since Illinois does not have a standardized PMS, local highway agencies are able to select a PMS that meets their needs and budget. Furthermore, IDOT does not require use of a specific pavement condition rating to trigger project selection. By giving local highway agencies flexibility, both large and small agencies should be able to effectively build a viable pavement preservation program.

Procurement Using Federal Funds

With the current economy and escalating construction costs, many Illinois highway agencies have budget limitations. IDOT's pavement preservation process facilitates the use of federal funds for treatments that have historically been considered ineligible for federal funds in Illinois. Many agencies do not use federal funds on an annual basis for pavement preservation. Instead, federal funds are often reserved for large projects every several years. The federal bidding requirements and other regulations are often different than Illinois state requirements. With these differences, a challenge exists in providing a thorough process for the use of federal funds for preservation treatments.

BLRS, with assistance from the IDOT District Office, reviews all federally funded projects to ensure compliance. Currently, five of nine IDOT District Offices have assisted with implementing pavement preservation on the local system. These five IDOT District Offices have been an integral part of development of the draft local pavement preservation policy.

Statewide Specifications

Since pavement preservation has not been fully implemented on the state or local system, statewide specifications are not available for several of the pavement preservation treatments. Therefore, local agencies are often relying on contractors or material suppliers for specifications.

BLRS is working closely with the BMPR, industry associations, and local highway agencies to develop statewide specifications. Statewide specifications ensure fair and competitive bidding, approved materials, and uniform construction techniques.

State-Level Implementation Challenges

At the state-level, IDOT continues to move slowly, but steadily, toward using pavement preservation to effectively manage the highway network. In doing this, IDOT faces four main challenges:

- Inadequate funding for highway maintenance;
- Condition of the highway network;
- Proper preventive maintenance treatment selection; and
- Public perception.

Inadequate Funding

Similar to most other states and agencies, IDOT is finding it increasingly difficult to maintain the highway network with the available funding. Traditionally, IDOT has used varying thicknesses of HMA overlays to renew pavement surfaces. Depending on the pavement's condition, the HMA overlay thickness has been 1.5 in. or greater. Programming guidelines based on condition and other factors were used to determine the necessary thickness.

This same process is used today, but due to the high cost of HMA, IDOT is finding it difficult to use HMA overlays as was done in the past. The increased cost is causing IDOT districts to use thin HMA overlays more frequently and delay some resurfacing projects in order to complete others. The use of less expensive treatments, such as the preventive maintenance treatments, is being looked at as a way to stretch the dollar. Moving toward using preventive maintenance treatments will help to maintain the highway network, but other challenges remain, such as problems with project selection, treatment performance, and a general resistance to preservation treatments.

Condition of the Highway Network

For many years, IDOT managed the highway network using a worst first strategy and placement of HMA overlays. When funding is plentiful and material costs are reasonable, this strategy can somewhat maintain an appropriate LOS. However, when funding is low and material costs are high, this strategy cannot keep the overall condition of the highway network at a level that meets public approval. When economic factors are combined with other decisions made in an organization, the uphill climb to improve overall network condition becomes increasingly difficult.

During the past few years, IDOT has made a conscious decision to move funding toward bridge projects in order to maintain a high percentage of Illinois bridges in good condition or better. Bridge work is very expensive and absorbs a large portion of construction program funds. In funding these projects, IDOT districts are forced to delay pavement rehabilitation projects beyond the typical condition levels at which rehabilitation would be performed. In doing this, fewer and fewer pavements are candidates for the lower cost treatments because their condition has deteriorated to a level that cannot be effectively treated by these methods.

Proper Preventive Maintenance Treatment Selection

Most state-maintained routes were originally constructed as continuously reinforced concrete, jointed reinforced concrete, or jointed plain concrete pavement. Later in their service lives, HMA overlays were placed to provide a new riding surface and to slow the deterioration of the concrete. A primary distress of jointed concrete pavements is reflective cracking. Using reflective crack control treatment with the HMA overlay can slow the reflection of the cracks, but it cannot eliminate the distress.

With IDOT looking at using preventive maintenance treatments to stretch construction funds, treatment selection becomes difficult. Preventive maintenance treatments are better suited for flexible pavements. Composite pavements do not perform as well with preventive maintenance treatments due to reflective cracking. The slurry treatments are thin and brittle, which allow the cracking to reflect through early in the service life of the preventive maintenance treatment. IDOT is using these treatments, but the reflective cracks are still the primary distress of the pavements and the service lives of these treatments are not as long as desired. For pavement management purposes, IDOT is still trying to determine the service lives of these treatments.

Public Perception

One final challenge faced by IDOT is public perception. As mentioned previously, IDOT traditionally used HMA overlays of varying thicknesses to maintain the highway network. The pavement was left in service as long as possible without treatment, and then a HMA overlay was placed to bring the surface back to a new condition. If constructed properly, new HMA overlays have a good appearance and ride well.

There are a few issues that are causing the motoring public to have a difficult time understanding the philosophy of preventive maintenance. The first issue is the type of treatment being used for preventive maintenance. The public has become accustomed to Illinois roads being treated with a HMA overlay. Thickness of the overlay varied based on the condition of the pavement (1.5 in. for better condition pavements—SMART overlay, 3.75 in. for policy overlay, ≥ 4 in. for structural overlay), but some type of overlay was usually placed to bring the pavement back to new condition. Because one treatment has been used extensively in the past, many residents believe that any other type of treatment is inferior.

Another issue is the timing of treatment placement. Following the pavement preservation philosophy, preventive maintenance requires the pavement to be in good condition when applying the treatment. This means leaving some pavements in poor condition until rehabilitation is required. Because of the worst first approach used by IDOT for so many years, the public does not understand why one pavement in good condition would receive a new treatment when a nearby pavement in poorer condition is ignored. All of these challenges are difficult; however, IDOT is working to overcome them.

CONCLUSIONS

As in other states, there are many reasons why IDOT has recently embraced pavement preservation. These include addressing the challenge of maintaining a large network of public roads with an increasingly shrinking budget, as well as recognition that there are benefits to both the agency and users to be derived from a well-designed pavement preservation program. There are several elements of Illinois' program, however, that are unique. These include the role of industry in successfully spearheading the initial development of the pavement preservation program and the joint efforts of the BLRS and BMPR to develop guidelines on project and treatment selection that could be used to improve pavement preservation practices. The introduction of the program through a statewide training initiative is also an important part of IDOT's program.

Moving forward, there remain many challenges. Confusion over previous programs that used the term preservation but included the use of nonpreservation techniques, such as HMA patching and pavement rehabilitation, has created a challenge in introducing the pavement preservation program. Also, the lack of a statewide pavement management program with detailed forecasting and program alternative comparisons causes additional challenges. If a full PMS existed, the benefits associated with a preventive maintenance program could be better documented and used to demonstrate that it is more cost effective to invest in maintaining pavements in good condition as opposed to using a worst first strategy of fixing roads once they are in poor condition.

From the state-level, the initial program supported by industry initiatives covers a limited number of preventive maintenance treatments. Treatments not supported are not allowed with appropriated funds, effectively creating an artificial restriction on treatment use. The available treatments should only be limited by their efficacy, cost effectiveness, and availability. IDOT's toolbox needs to be expanded to cover the full range of treatments that may provide benefits in Illinois.

The initial treatment guidelines have been developed based on best practices nationwide. Ideally these would be modified over time to reflect Illinois experience. This is especially the case for the portion of the guidelines that specifically addresses the conditions under which the use of the treatments is recommended and the expected performance of the treatment. The knowledge base that would be used to modify the guidelines would need to come from the use and careful monitoring of the performance of the preventive maintenance treatments.

There is reluctance, both within the public agencies and among the traveling public, to move away from the use of HMA surfacings. There is a long history in Illinois of the almost exclusive use of HMA to maintain and rehabilitate all pavement types, and the alternatives are not as widely accepted.

Technology transfer also remains a key to the long-term success of pavement preservation in Illinois. Both the state and local agencies need to learn about the use of preventive maintenance treatments. Important topics to continue to cover include the following:

- Project selection,
- Treatment selection, and
- Program benefits.

It is clear that successful pavement preservation in Illinois is going to be the result of a long-term effort. The early initiatives are important first steps and have laid the necessary groundwork for moving forward.

Outsourcing and Safety Issues

Outsourcing
What Are You Prepared to Do About It?

MARSHALL STIVERS
Infrastructure Corporation of America

"Even if you're on the right track, you'll get run over if you just sit there."—Will Rogers

Outsourcing, privatization, public–private partnerships, P3, CDA—whatever it's best known as—has become an increasing subject of discussion in the United States. The trend toward the outsourcing of routine highway maintenance is frequently considered as an optional workforce to help accomplish a portion of the highway agency routine maintenance workload.

Following are some of the factors influencing outsourcing:

- **A rising cost of routine maintenance for repairs to the aging highway and bridge system.**
- **Gasoline tax receipts, while increasing, have not kept pace with inflationary trends or the increasing demand for more highways.**
- **Government agencies are not being authorized an adequate number of positions to design, construct, maintain, and operate the infrastructure required to meet public demands on the highway system.**
- **Foreign investors are increasingly available to invest capital in the U.S. highway system.**
- **In its recently released final report, the National Surface Transportation Policy and Revenue Study Commission described a plan to "increase investment, expand services, repair infrastructure, demand accountability, and refocus federal transportation programs, while maintaining a strong federal role in surface transportation."**

Following are some items for consideration when considering outsourcing of maintenance work:

- **Performance measures: a method of measuring the quality of work being performed is encouraged.**
- **Desired results: a performance measure requirement should clearly identify the intended end result condition.**
- **Existing costs: agency costs of accomplishing the specified work are valuable in determining whether a bid is cost-effective. Similarly, the agency should ensure that its cost data reflect the actual costs of accomplishing the desired results within the project limits.**
- **Unforeseen occurrences: repairs for damages due to fires, floods, snowstorms, hurricanes, civil unrest, etc., are a real and potential cost item for an agency as well as a contractor.**

The problems confronting the highway maintenance community today aren't unknown nor are many of the solutions beyond comprehension. Unfortunately, there is no silver bullet; the challenges are many and difficult, and the physical infrastructure is under a tremendous strain. The only question remaining is what are we prepared to do about it?

Pavement Striping Visibility in Wet Conditions

VINCENT LIU
Utah Department of Transportation

Pavement striping visibility in wet conditions has always been a problem for motorists. The problem is much worse at night when water film on the pavement surface reflects light in random directions rather than back to the driver. In consideration of active winter maintenance activities in Utah, the thickness of pavement markings above the road surface is limited, because above-ground markers cannot be used. This creates a difficulty for all motorists, and particularly older drivers, to see pavement markings under wet, night road conditions. The Utah Department of Transportation (UDOT) is conducting a wet, night roadway visibility study. UDOT has identified several different methods to improve pavement markings' visibility under wet, night roadway condition. These methods will be implemented and installed in summer 2008. UDOT will perform field tests, inspect, and analyze each of these methods in the coming year. These methods are include (*a*) install recessed–plowable pavement markers with active light source; (*b*) groove and install pavement marking materials; (*c*) use new wet, night materials with glass beads on waterborne paint.

Variable Speed Limits Signs
Effects on Speed and Speed Variation in Work Zones

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Variable speed limit (VSL) signs are used across the country in conjunction with intelligent transportation systems to lower posted speed limits in areas affected by conditions such as congestion, construction, accidents, fog, snow, and ice. VSL signs allow operators to adjust the posted speed limit without changing the physical sign. As technology advances, the ease of using VSL signs is also increasing since speeds can now be changed at preset times via e-mail or telephone, or manually at the site. The Utah Department of Transportation desired to evaluate the effectiveness of this technology on driver behavior before using it widely in work zones on state highways. The focus of this research is driver response to VSL signs. A six-mi-long test site with a long-distance work zone on I-80 north of Wanship, Utah, was used to test drivers' responses to VSL signs. Five speed detectors and two VSL signs were placed in this zone and vehicle speeds were monitored for about 3 months. The speed data analyses showed that driver response was positive. Though the average speeds between static speed limit signs and VSLsigns were not statistically different at a 95% confidence level, variation in speeds was reduced in general, especially at the first speed detector location downstream of the first VSL sign. Providing drivers with speed restrictions that reflect actual conditions builds trust in the posted speed. Long-term use of VSL signs is recommended for evaluating their long-term effect on driver compliance to reduced work zone speed limits.

Variable speed limit (VSL) signs are used across the country in conjunction with intelligent transportation systems to lower posted speed limits in areas affected by conditions such as congestion, construction, accidents, fog, snow, and ice. VSL let operators adjust the posted speed limit without changing the sign.

The Utah Department of Transportation (UDOT) desired to test the use of VSL signs in a construction project. Long construction zones often have actual construction occurring in only short segments of the zone, but they use static speed limit signs as if construction occurs throughout the entire construction zone at all times. In reality, the intensity, duration, and location of construction vary throughout the zone. Providing variable speed restrictions based on the level of construction improves safety and provides more accurate information to drivers, helping them comply with the posted regulatory speed.

Reducing vehicle speeds in construction zones improves safety for drivers and construction workers and can reduce the severity of crashes that occur in the zone. While it is true that crashes involving vehicles traveling at high speed are more severe than those at low speed (*1*), reducing the speed of individual drivers is important and the variation of the speed among all drivers increases safety even more (*1*). Studies show that regardless of the average speed on a highway, the more a vehicle deviates from the average speed, the greater its chances of crashing (*1*).

The purpose of the study is to investigate the applicability and effectiveness of VSL signs at work zones in Utah. The study attempts to answer the question, would the use of VSL signs better control the variability of vehicle speeds by providing drivers with more accurate information, particularly during construction periods? Figure 1 shows the type of VSL sign used in the study.

This paper presents a brief literature review, study methodology, study findings, and conclusions and recommendations.

LITERATURE REVIEW

VSL signs have been used for both non-work zones and work zones. The Washington State DOT utilizes a VSL system on an I-90 mountain pass that responds to weather conditions to advise motorists of safe speed limits. It has also instituted a VSL system on a 23-m section of US-2 that alters speed according to road conditions (*2,3*). Many other transportation agencies have used this technology to reduce speeds on roads. On the New Jersey Turnpike, 120 signs over 148 mi display variable speed limits based on speed and volume data collected by inductive loop detectors (*2*). New Mexico had a VSL system on an urban section of I-40 from 1989 until 1998 that used traffic speed, time, and precipitation to determine safe speed limits (*2*). In Colorado, at the Eisenhower Tunnel on I-70, west of Denver, VSL technology weighs downhill-traveling trucks and advises the truck drivers to reduce their speed. Evidence suggests that since VSL

FIGURE 1 Variable speed equipment used in the study.
(Photo by Thomas McMurtry, July 2007.)

system deployment, truck-related accidents have declined on steep downhill sections, while volume of truck traffic has increased by an average of 5% per year (*2*). Oregon also uses a similar system for downhill trucks on I-84 (*2,4*).

As for use of VSL signs in work zones, the Washington State DOT has used them to inform drivers about the reduction of speed limits in work zones; for instance, they use VSL signs to change the speed limit from 70 mph to 60 mph. Minnesota DOT uses VSL signs in work zones on I-494 in the Twin Cities area to decrease upstream traffic speed from 65 mph to 45 mph when drivers approach the work zone bottleneck (*2, 5*).

STUDY METHODOLOGY

Hypothesis

As has already been shown improved safety to motorists and construction personnel occur when drivers follow predictable patterns and speeds. VSL signs, which adjust the speed limit based on conditions, will have greater compliance than static signs. This compliance will result in more drivers traveling within the posted speed limit and fewer drivers traveling either significantly faster or slower than the posted speed. In this study, the average speed and speed variation around the average speed were used as performance evaluators instead of the 85th percentile speed and its variation because the average speed was closer to the posted speed limit.

Study Site Location and Construction Project Description

The study site was located on I-80 in Summit County near the Utah–Wyoming border. The annual average daily traffic (AADT) of this section of I-80 was 13,280 in year 2007. Single-unit trucks accounted for 5% and combination trucks accounted for 43% of the AADT. This study site was chosen because it became an active construction area just prior to the data collection. This study site had a pavement crack and seal work zone from milepost 185 to 191, with lane closures in both the eastbound and westbound directions. Travel in both directions was restricted to one lane through the work zone at all hours for the duration of the project—from summer to fall 2007. For this study, only westbound traffic was used due to steep, continual upgrades on the eastbound lanes that slowed traffic significantly. The vertical alignment of the westbound direction was milder than the vertical alignment of the eastbound direction.

Data Collection

Vehicle speed data were collected from July 10, 2007, through September 29, 2007, at five locations on westbound I-80, accounting for all hours of the day, every day during this time. Data were collected using Jamar tube counters. Traffic-counting tubes were used due to accuracy of defined speed bins, although maintenance requirements were high. There were several occasions when the tubes were removed for paving or were torn out by traffic. The data collection period was set at 12 weeks to account for losses and to accurately count all roadway scenarios.

Five locations were chosen to give a representative spectrum of speeds under multiple conditions of the construction zone. Figure 2 shows a map of the study section including the speed counter locations and VSL sign locations. The first counter was placed upstream of the

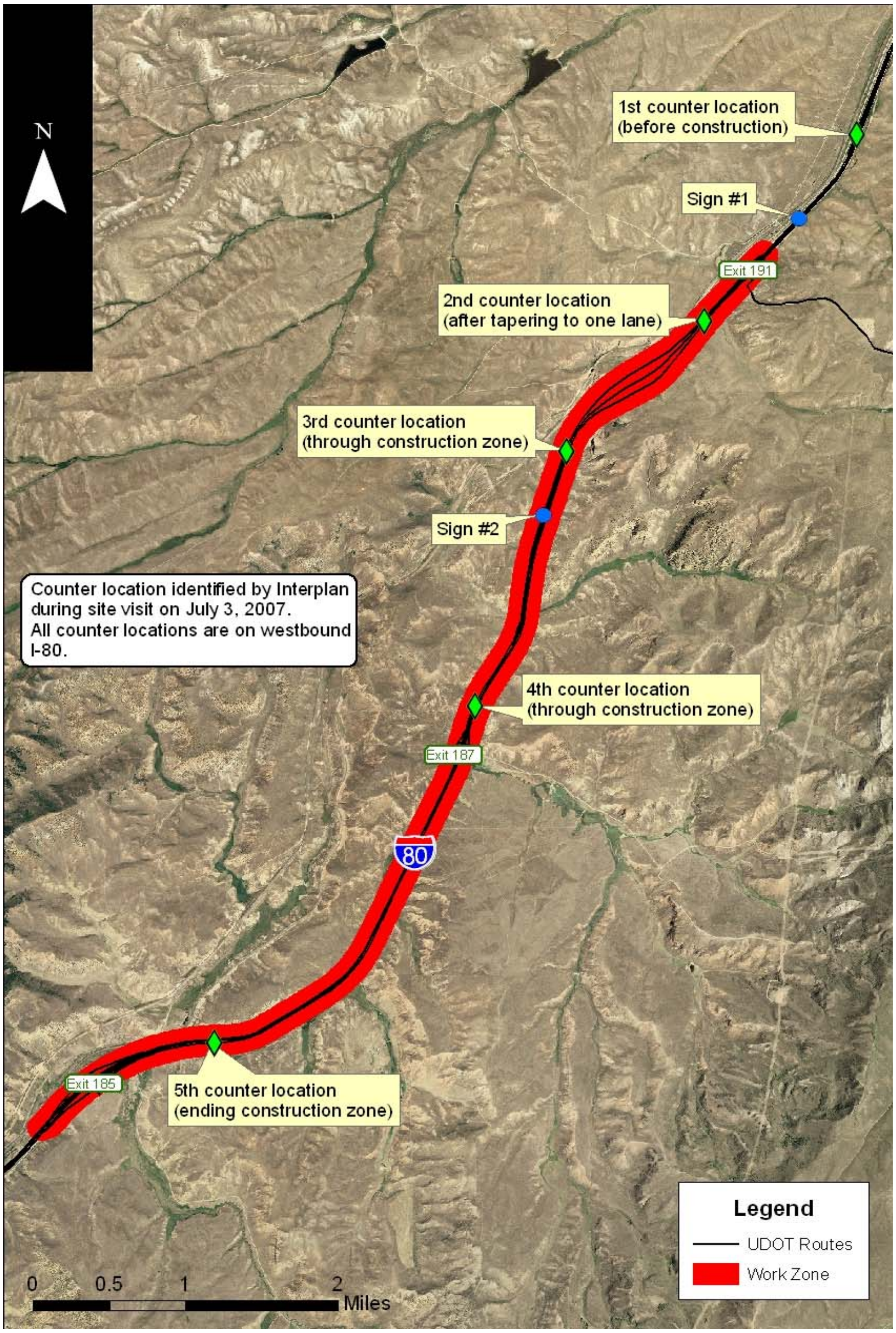


FIGURE 2 Location of the VSL signs and sensor locations. [Source: Geographic information system data from Utah Automated Geographic Reference Center (*7*).]

construction to capture vehicles under normal conditions. The second counter was placed at the beginning of the construction zone just after the roadway was tapered down to one lane. The third and fourth counters were placed throughout the construction zone, in no specific locations, but they were spaced about a mile and a half apart. The fifth counter was placed near the end of the construction zone where there was still only one lane open, but not in active construction. The construction work moved along the work activity area during the data collection period. The size of the speed limit sign was 30 in. by 36 in., which was smaller than the size 48 in. by 60 in. defined by the *Manual on Uniform Control Devices* (*6*) and the size of each digit was 18 in. by 12 in. (See Figure 1 for the VSL sign used in the study.)

For the purpose of this study, two VSL signs were tested against the existing static sign. UDOT did not allow the speed limit for this segment of I-80 to be reduced from 75 mph to 55 mph using a standard static 55 mph speed limit sign. They did, however, allow the use of VSL signs showing 55 mph speed limit because the reduction was made for a research purpose. Speed data were collected, hence, under the three different conditions listed below.

- Standard 65 mph speed limit sign,
- VSL sign posted at 65 mph 24 h per day, 7 days per week, and
- VSL sign varying between 55 mph during the day and 65 mph at night.

Data were collected for the standard 65 mph sign for the first 3 weeks of the testing period. Following that, the two VSL conditions were alternated in 2-week blocks. The schedule of the data collection is displayed in Figure 3.

STUDY FINDINGS

Data Points

The data were collected in 5 mph intervals for each hour of the day throughout the study. Analysis could be performed, therefore, to answer specific questions. For instance, a question such as how many vehicles traveled between 55 and 59 mph on Tuesday from 9 to 10 a.m. at counter number 3 could be answered by the data collected in the study. Data indicating the type of vehicle (truck, trailer, recreational vehicle, motorcycle, etc.) were not collected. Periods where data were not collected, generally due to equipment malfunction when tubes were stripped off the pavement, occurred randomly by date, time, and counter.

Speed Distribution

The distribution of speeds observed at various counters followed an expected bell-shaped curve; however, speed distribution was more coherent with VSL signs than with regular static speed limit signs. Figure 4 shows the difference between the two methods. It should be noted that these show speed distributions of typical 1-day data. Figure 4*a* shows speed distributions at the five counters on Thursday, July 12, 2007, when the 65 mph speed limit was presented by regular static speed limit signs; Figure 4*b* shows speed distributions at the five counters on Thursday, August 30, 2007, when speed limit was presented by VSL signs. As seen in these two plots, there are two distinct speed groups with VSL signs: one bell-shaped distribution for Counter 1 upstream from the work zone, where the speed limit was 75 mph, and the other bell-shaped distributions for the counters within the work zone, where speed limit was 65 mph. As far as

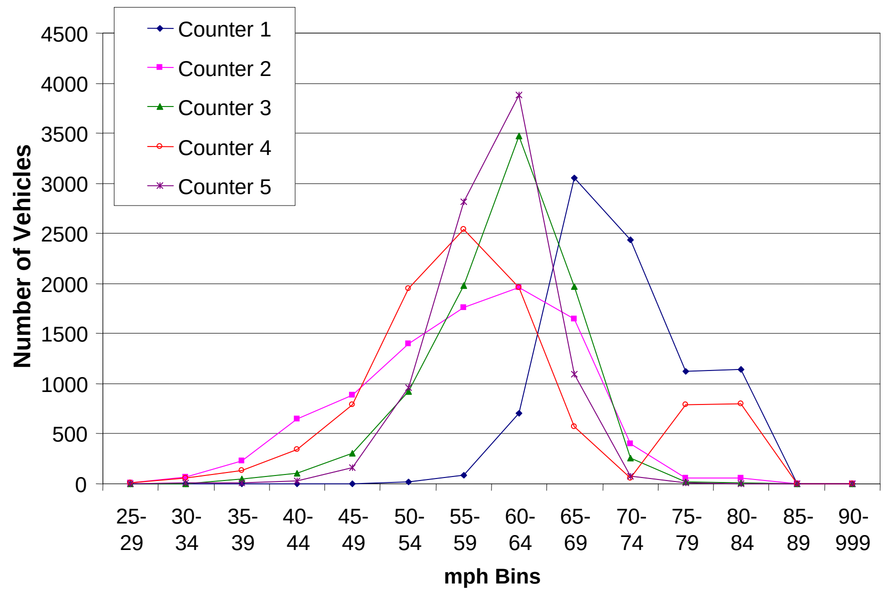
Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
			JULY			
CONSTRUC-TION ON-GOING	2	3	4	5	6	7
8	STANDARD SIGN 65 MPH 24/7	10	11	12	13	14
15	16	17	18	19	20	21
22	23	24	25	26	27	28
			AUGUST			
29	30	VSL 65 MPH 24/7	2	2	3	4
5	6	7	8	9	10	11
12	VSL 65 MPH NIGHT 55 MPH DAY	14	15	16	17	18
19	20	21	22	23	24	25
			SEPTEMBER			
VSL 65 MPH 24/7	27	28	29	30	31	1
2	3	4	5	6	7	8
9	VSL 65 MPH NIGHT 55 MPH DAY	11	12	13	14	15
16	17	18	19	20	21	VSL 65 MPH 24/7
23	24	25	26	27	28	29

FIGURE 3 Data collection schedule.

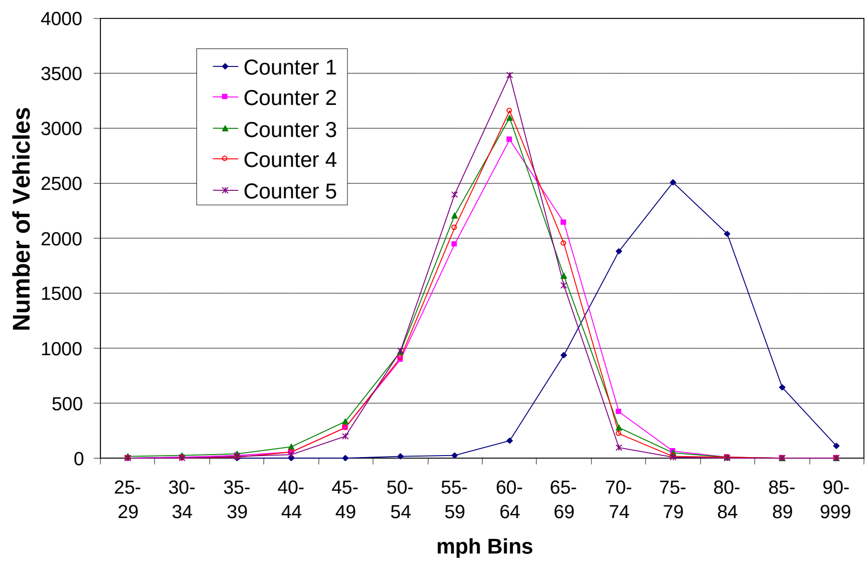
these 2 days are concerned, the speed distribution with VSL signs appears more consistent than that with static speed limit signs.

Standard Deviation of the Data

Examination of the daily standard deviation of speed showed that, for the most part, Counter 1 had larger standard deviation than the other counters after the VSL signs were installed, as shown in Figure 5*a*. This was expected because vehicle speeds in the merge area leading into the work zone tend to vary more than in the work zone itself. After the VSL signs were installed on July 31, Counter 1 had the highest standard deviation 31 of the 50 days with complete data, or 62% of the time. Between August 13 and 20 and between September 10 and 20, Counter 1's standard deviation was lower than the other counters. This may be because construction on those days frequently interrupted traffic in the work zones, leading to greater deviation in speed at the remaining counter locations and making the variation in speeds at Counter 1 smaller than the other counters. In July, however, Counters 2, 3, and 4 had unusually high standard deviations. Wide speed fluctuations during heavy construction were expected. The level of construction

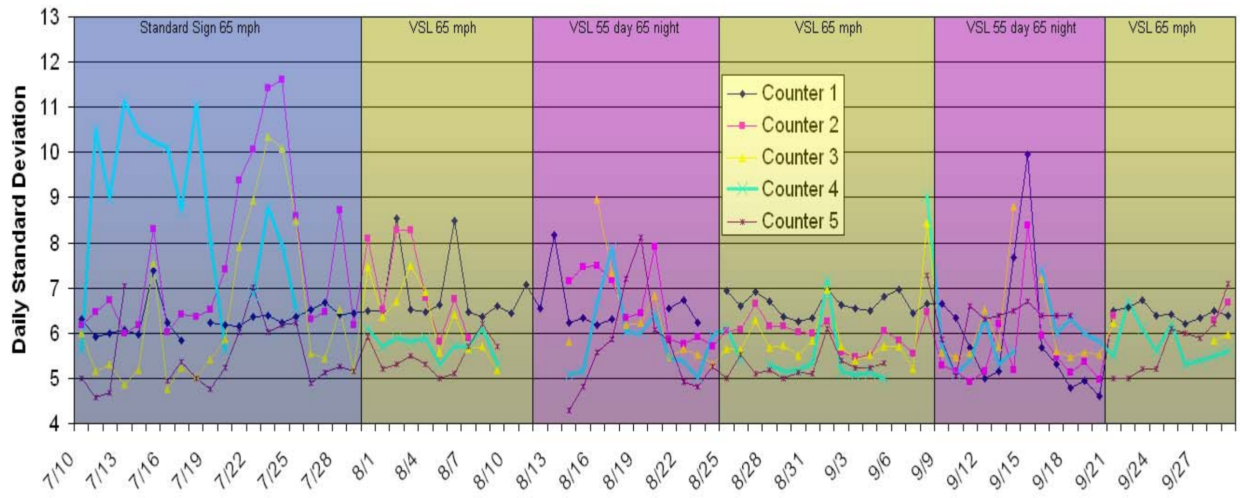


(a)

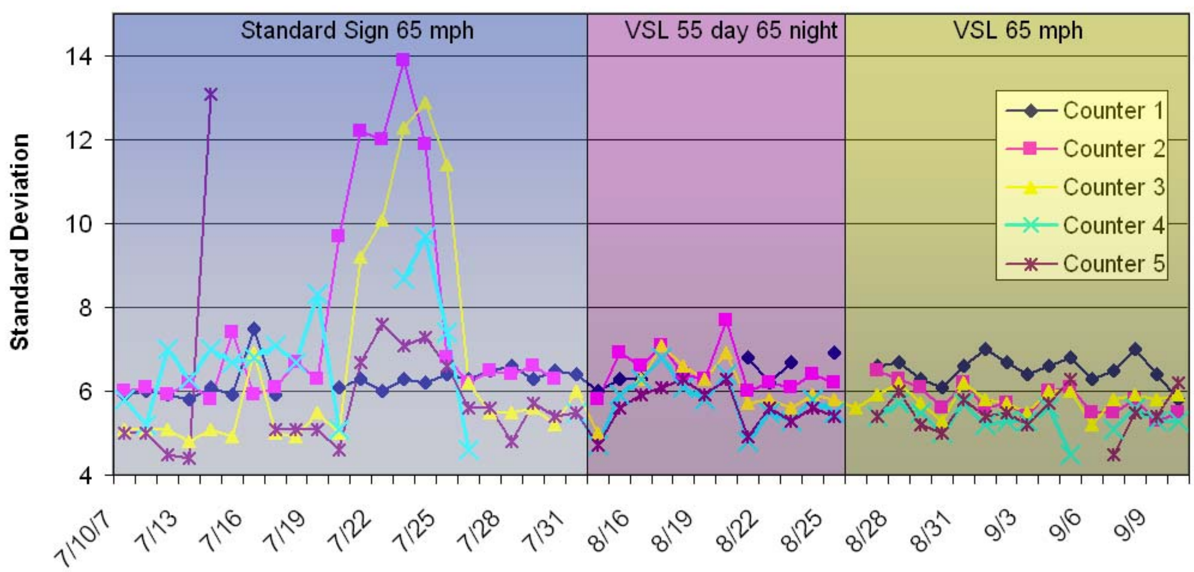


(b)

FIGURE 4 Comparison of speed data distribution under different speed limit presentation: (*a*) Thursday, July 12, 2007, static 65 mph sign all day; and (*b*) Thursday, August 30, 2007, VSL sign 65 mph all day.



(a)



(b)

FIGURE 5 Standard deviation of speed: (*a*) standard deviation of speed during the entire data collection period; and (*b*) nighttime standard deviation of speed.

activities during the day (there was no construction at night), however, could not be separated from the data in any methodical way.

This study sought to compare the variability of speeds under different speed limit sign presentation methods. Therefore, to examine speed variation without construction interruptions, the nighttime (from 7 p.m. to 8 a.m.) standard deviation was also analyzed.

Nighttime standard deviation was highest at Counter 1 when VSL signs were present, as shown in Figure 5*b*. Between July 20 and July 27, when the standard static 65 mph sign was used, standard deviations at Counters 2 and 3 were unusually high, which could have been caused by unusually high traffic on this stretch. There was very little construction during nighttime hours and there was no crash within the work zone, according to the engineer's diary. Of the 22 days with complete data, from August 13 through September 9, Counter 1 had the highest standard deviation for 16 days, or 70% of the time. This is a slightly higher percentage than found measuring full 24-h periods.

Before the installation of VSL signs, Counters 2 through 5 had speeds with daily standard deviation ranging from 4.3 mph to 14 mph. After VSL signs were installed, the highest daily speed standard deviation was 7.9 mph, about one half of the maximum standard deviation experienced before VSL signs were used. A typical standard deviation expected for this type of highways without work zone is about 50 mph. The graph in Figure 5*b* also demonstrates that when the VSL sign was set to 65 mph, standard deviation for Counters 2 through 5 was greater than 65 mph on only three occasions. This low standard deviation of average speeds indicates that few vehicles were moving either much faster or much slower than other vehicles.

Average Speed

In order to find trends when construction was underway, daytime average speeds were analyzed and are presented in Figure 6. Daytime average speeds at Counters 2 through 5 were less than at Counter 1, except for a short period in September. Counter 1 was located at the 75 mph speed limit segment, while all other counters were placed at 65 mph or 55 mph speed limit segments as shown in Figure 6. Slow speeds in September at Counter 1 might have been due to congestion just upstream of the work zone. One possible reason is an increase in upstream demand. Counter 5, on the other hand, experienced very high average speeds during that period, and other counters exhibited average speeds lower than during other periods. Increased speeds at Counter 5 may reflect vehicles speeding up significantly to make up for time lost in congestion upstream.

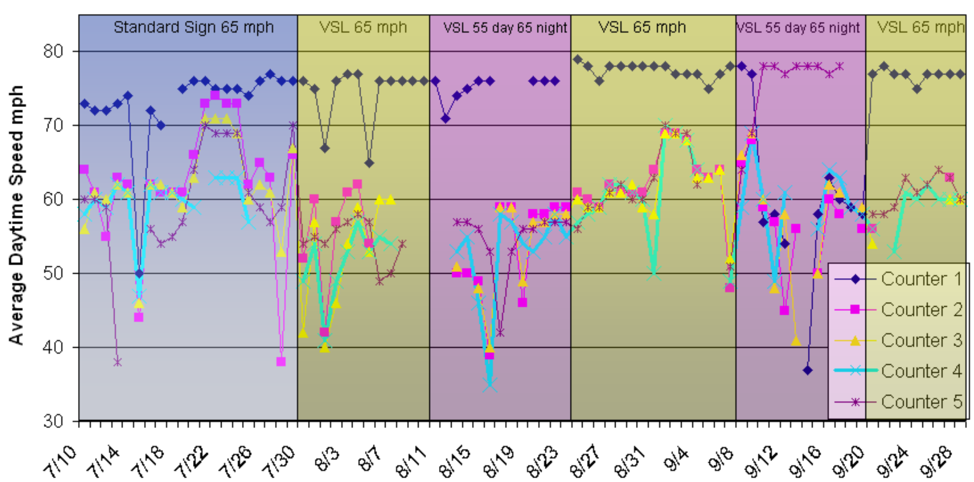


FIGURE 6 Daytime average speed, July 10 to September 28.

Nighttime Average Speed

To evaluate the effect of VSL signs without construction work, average speeds from 7 p.m. to 8 a.m. at the five counter locations were plotted. With the static 65 mph work zone speed limit sign, average speeds varied, as shown in Figure 7*a*. The standard deviation of the average speeds at each counter location varied from about 1.5 mph to 5.0 mph. Ten samples were obtained to evaluate the effectiveness of regular static speed limit signs. The static limit at Counter 1 was 75 mph, while it was 65 mph at Counters 2 through 5. Not all days had complete data; the days listed in the figures were selected from those that had complete data for a 24-h period.

As Figure 7*a* illustrates, Counter 1 recorded average speeds between 70 and 75 mph, which was expected. Between Counters 2 and 4, there was a general trend of decreasing average speeds in the work zone; however, at Counter 5, speeds actually increased. Figure 7*a* shows that there were wider variations of average speeds during the nighttime with regular static signs as compared to VSL signs.

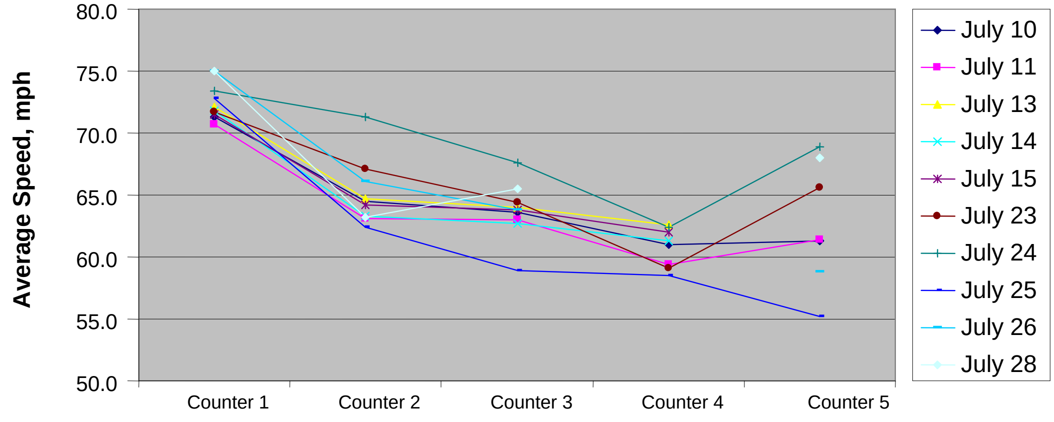
With VSL signs displaying 65 mph, reductions in average speeds were consistent at each location, as shown in Figure 7*b*. The standard deviation of the mean at each counter location varied from about 0.5 mph to 1.0 mph, indicating that at night, drivers are more responsive to the reduced speed limit with VSL signs than with static speed limit signs. One potential reason could be that the lighted VSL speed limit signs are visible much further away than the static speed limit signs, increasing the compliance level.

Daytime Average Speed

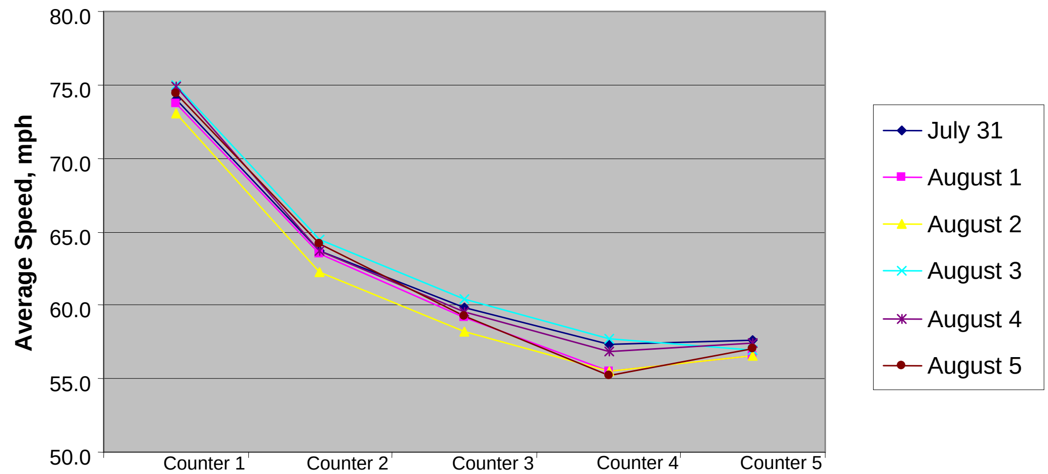
Daytime data from 9 a.m. to 7 p.m. were used for this analysis to avoid the transition period from nighttime to daytime traffic, that is, 8 a.m. to 9 a.m. During the day average speeds were affected by the magnitude of work underway in the work zone, as shown in Figures 8*a* and 8*b*. Some of the days show that average speeds were significantly lower than at other locations. Figure 8*a* shows the trend in average speeds at each counter with the static speed limit sign, and Figure 8*b* shows the trend in average speeds at each counter with VSL signs. In general, speed changes were more consistent with VSL signs than with static speed limit signs. These two daytime average speeds and their variances were compared using an *F*-test and a *t*-test. The analysis results are shown in Table 1.

F-tests for the five counters showed that the differences in speed variance at Counters 1 and 2, for the static 65 mph speed limit sign and the VSL 65 mph speed limit sign, were statistically significant. Inversely, at the other three counters, the differences in speed variance were not statistically significant at a 95% confidence level. This means VSL helped reduce the speed variation at Counters 1 and 2. *T*-tests for the five counters showed that the differences in average speed were significant at a 95% confidence level at Counter 1 but not significant at the other counters.

Figure 8*c* shows the trend in speed reduction with VSL signs displaying a 55 mph speed limit. Because static speed limit signs showing 55 mph were never shown to drivers, it was not possible to compare the benefit of VSL signs over static speed limit signs at the 55 mph speed limit level. However, it is obvious that with a 55 mph speed limit, drivers slowed down, although not to 55 mph. They also tended to speed up at the downstream end of the work zone, as demonstrated by the average speeds at Counter 5. Four samples started with 75 mph at the



(a)



(b)

FIGURE 7 Nighttime average speed comparison: (*a*) nighttime average speed, July 10–28; and (*b*) nighttime average speed, July 31–August 5.

TABLE 1 Results of *F*-Test on Variances and *t*-Test on Sample Means

	Static 65 mph Daytime			VSL 65 mph Daytime			*F*-test on Variance	*t*-test on Two Sample Means
	No. of Samples	Mean	SD	No. of Samples	Mean	SD	*p*-value	*p*-value
Counter 1	10	75.00	1.71	14	77.11	0.98	0.032	0.004[1]
Counter 2	10	59.86	11.97	14	63.76	3.57	<0.001	0.341[1]
Counter 3	10	60.05	9.21	14	61.53	6.80	0.156	0.654
Counter 4	10	58.64	5.21	14	61.61	6.75	0.426	0.357
Counter 5	10	61.44	7.06	14	63.06	5.42	0.202	0.561

[1] Two-sample assuming unequal variance.

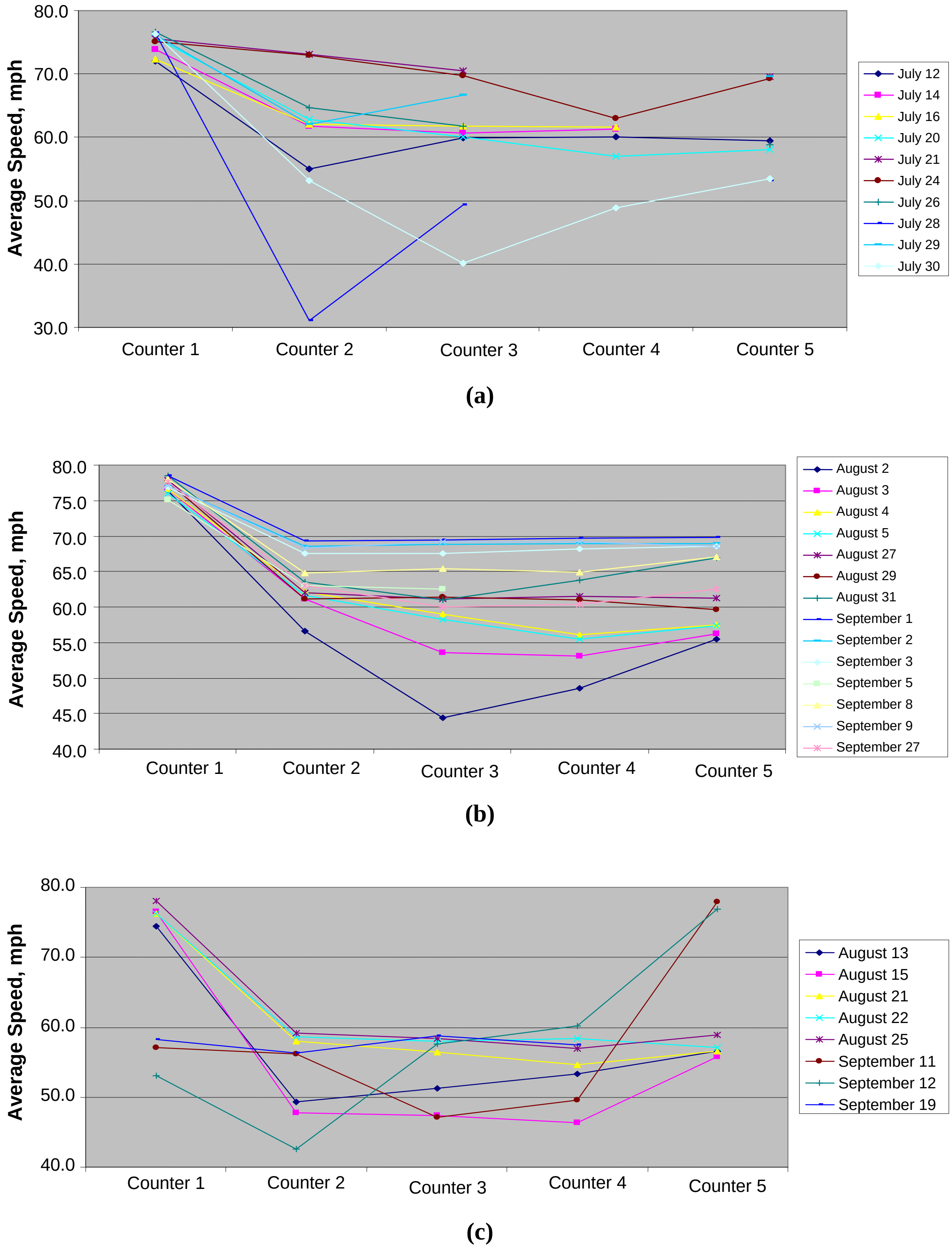


FIGURE 8 Daytime average speed comparison: (*a*) daytime average speed, July 12–30, 65 mph static speed limit sign; (*b*) daytime average speed, August 2–September 27, 65 mph VSL sign; and (*c*) daytime average speed, August 13–September 19, 55 mph speed limit sign.

upstream of the work zone, and their speeds decreased to 50 to 60 mph. As shown in Figure 8*c*, drivers maintained that speed until they passed the active work zone. One day (September 12) started with a lower average speed (53 mph) upstream of the work zone. It is likely a slow-moving queue formed upstream, and drivers seemed to become impatient and sped up at Counter 3. Near Counter 5, they sped up to 77 mph (see Figure 8*c*).

Speed Limit Compliance

If the average speed of travel is recorded for each hour at each data collection point for the entire length of the study, the observed speed can be compared to the posted speed limit. Figure 9 shows, by counter and by posted speed limit, the percentage of vehicles obeying the speed limit. At Counters 2, 3, and 5, the VSL at 65 mph has greater compliance than the static 65 mph signs. At Counter 4, the static sign has 100% compliance for hourly average speed of travel. At all the other counters, however, the VSL signs posted at 55 mph have the worst compliance rate.

Statistical Analysis on Speed Change from Nighttime 65 mph to Daytime 55 mph

The previous discussions on speed reduction from 75 mph to 65 mph approaching the work zone indicated that both speed reduction signs (static 65 mph versus VSL 65 mph) could achieve necessary speed reductions, although VSL signs also reduce speed variances. This section presents some of the statistical analyses on speed changes.

Because it is hypothesized that drivers comply with large speed reductions, *z*-tests were performed to see if drivers complied with the daytime 55 mph speed limit. Several days had complete data sets that allow for analysis of the transition from the nighttime 65 mph speed limit to the daytime 55 mph speed limit shown by VSL signs. Table 2 presents the results of *z*-tests

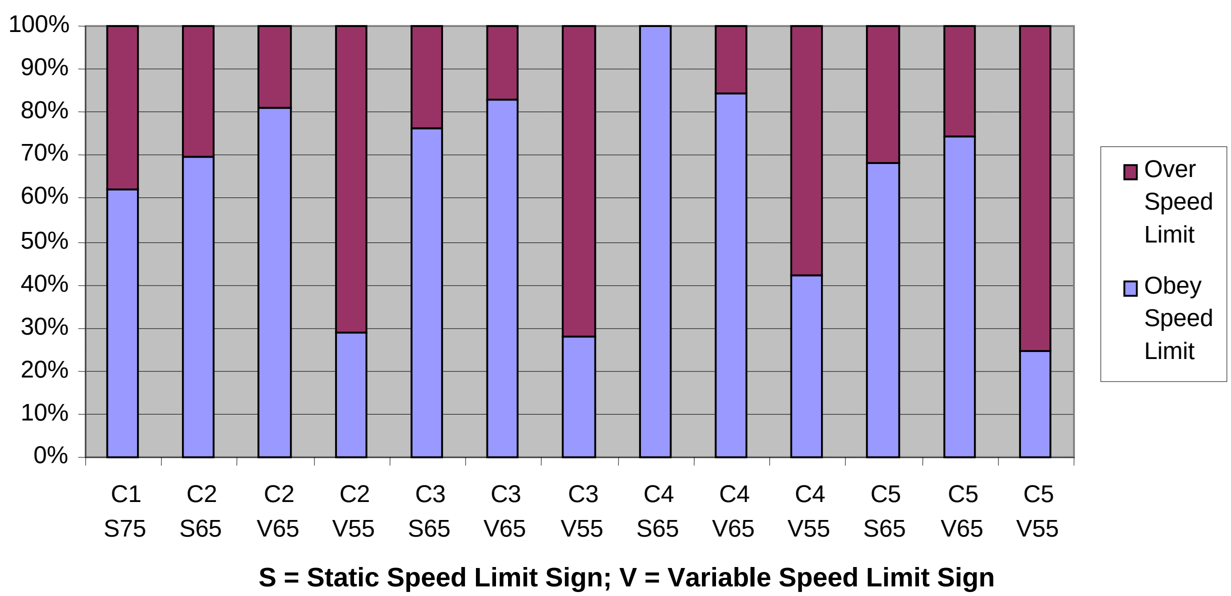


FIGURE 9 Speed compliance by hourly average speed.

TABLE 2 Statistics on Speed Reduction by VSL Signs, from Nighttime 65 mph to Daytime 55 mph Speed Limit: *z*-Tests on Mean Speed Differences at Counter 2 (Critical *z*-score = 1.65)

	Mean Speed Difference	Calculated *z*-Value	Significance Test
8/13/2007 Nighttime 65 mph to 8/14/2007 Z Daytime 55 mph	7.2	36.3	Significant
8/14/2007 Nighttime 65 mph to 8/15/2007 Daytime 55 mph	11.8	61.00	Significant
8/15/2007 Nighttime 65 mph to 8/16/2007 Daytime 55 mph	6.1	34.29	Significant
8/16/2007 Nighttime 65 mph to 8/17/2007 Daytime 55 mph	3.1	19.33	Significant
9/10/2007 Nighttime 65 mph to 9/11/2007 Daytime 55 mph	7.2	46.01	Significant
9/11/2007 Nighttime 65 mph to 9/12/2007 Daytime 55 mph	10.8	54.63	Significant
9/12/2007 Nighttime 65 mph to 9/13/2007 Daytime 55 mph	7.1	47.80	Significant

on speed differences between the two speed limits. As shown in the table, mean speed differences between the nighttime 65 mph and the daytime 55 mph speed limit were significant during these seven sample dates, indicating that drivers respond to large speed reductions.

To find out if drivers complied with the daytime 55 mph speed limit throughout the work zone, a data set, using VSL signs for the 55 mph speed limit, was extracted and analyzed. Table 3 shows the results of the *z*-tests. As shown in the table, in the upstream of the work zone at Counter 1, the average speed was 76.2 mph, statistically higher than the 75 mph speed limit at the 95% confidence level. Immediately after the first VSL sign, the average speed decreased to 58 mph. Although the difference between this value and the 55 mph speed limit is significant, the data shows that the sign still reduced average speed. At the remaining counters, the mean speed was close to 55 mph, although the difference between those speeds and the 55 mph speed limit was statistically significant. Nevertheless, drivers seemed to comply with the 55 mph speed limit throughout the work zone.

CONCLUSIONS AND RECOMMENDATIONS

This paper presented the results of a field test of VSL signs. The effect of VSL signs on drivers, as manifested by their speeds in the test work zone, was analyzed. The analysis showed that both types of speed reduction signs (static 65 mph versus VSL 65 mph) could achieve necessary speed reductions. VSL signs were, however, helpful in reducing speed variances near the entry to the activity area of the work zone (Counter 2 location). Speed variations at Counters 3, 4, and 5 were similar for both types of speed limit signs.

At night, when VSL signs were set to 65 mph and no construction activity was taking place, VSL sign data showed average speeds that were generally lower than static speed limit signs. Daytime speeds showed greater variation because of congestion and construction. However, even excluding the data impacts of low speeds during the daytime, VSL signs resulted in smaller speed variation than static speed limit signs near Counter 2, the entry point to the work zone activity area.

The potential concern of lower speed limits resulting in greater variation in driver speeds did not occur. At night, when VSL signs were set to 65 mph, the standard deviation of speeds

TABLE 3 Statistics on Speed Reduction by VSL Signs, from Nighttime 65 mph to Daytime 55 mph Speed Limit: Z-Tests on Mean Speeds with Daytime 55 mph Speed Limit for Work Zone by VSL Sign, Tuesday, 8/12/2007, between 9:00 a.m. and 7:00 p.m. (Critical Z-Score = 1.96)

Counter No.	No. of Samples	Mean Speed (mph)	Standard Deviation (mph)	95% Confidence Interval	Remarks
1	4,689	76.2	6.6	76.0–76.4	Statistically higher than 75 mph
2	4,921	58.0	5.6	57.9–58.2	Statistically higher than 55 mph
3	4,916	56.4	5.8	56.2–56.5	Statistically higher than 55 mph
4	4,919	54.6	8.0	54.3–54.8	Statistically lower than 55 mph
5	4,974	56.6	4.9	56.5–56.7	Statistically higher than 55 mph

NOTE: Counter 1 is in the 75 mph speed limit zone and the other counters are in the 55 mph speed limit zone. When the confidence interval does not contain 55 mph, the actual mean speed is either statistically higher or lower than 55 mph.

decreased to the 0.5- to 1.0 mph range, down from the 1.5- to 5.0 mph range evident with the static signs.

Although crash data were not directly collected, the results of this study imply that that VSL signs could contribute to reducing speed variation, especially near the entry of the work zone activity area, thus preparing drivers for the lower speed limit as they drive through the activity area. Reducing speed limit to 55 mph during the day seemed difficult, but the data showed that an average speed near 60 mph could be achieved. Providing drivers with speed restrictions that reflect actual conditions (construction underway during the day or no construction at night) builds trust in the posted work zone speed limit, thus increasing driver compliance with the posted speed limit and increasing work zone safety.

ACKNOWLEDGMENTS

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Management Systems

Data Collection, Maximizing Resources, and Pavement Knowledge Base

Use of PDAs to Capture Field Data for Input in North Carolina's Maintenance Management System

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The North Carolina Department of Transportation (NCDOT) recently conducted a feasibility study on the use of personal data assistants (PDAs) to collect employee and equipment time, work accomplishment, and work location information for input into their maintenance management systems (MMS). The application first allowed a crew leader to set up a crew (including personnel, equipment, and material), and download tasks (work orders) onto the device in an online mode. It then allowed the creation of tasks on the device in the field together with recording of the location, accomplishment, and durations for the crew for each task. The durations were then converted to editable "day cards" for crew and equipment that could then be uploaded along with any newly created tasks in online mode. The study involved two types of mobile devices: one small and compact,and the other larger and more rugged. An external Global Positioning System (GPS) device was attached to each device to determine locations. The study was conducted with a total of 15 PDA devices being used in the field for a total of between 5 and 8 weeks by five field units (for a total of almost 100 PDA weeks of use. A number of aspects were studied including general device preference, GPS use, and comparison of scheduled work orders versus those created in the field. The paper presents the study method, surveys, analysis of the data, and conclusions. In general, participants preferred the smaller PDAs to the larger and more rugged device. Of the total number of tasks that were uploaded, roughly half were scheduled in the MMS office and downloaded onto the PDA, and half were created directly on the PDA. It was possible to obtain a GPS location approximately 80% of the time and that these points had reasonable ground accuracy as shown by the fact that 95% of the time the point fell within 50 ft of a mapped road centerline with 80% within 10 ft. Study results show that despite early problems, most respondents found the GPS devices easy to use overall. The study was such an overwhelming success the mobile application has been enhanced and NCDOT planned to purchase about 1,100 new PDAs for distribution to field crews in 2009. This purchase has been delayed due to a budget shortfall within NCDOT. The study also supports the development of an interface to use MMS data to populate timesheets in SAP.

A maintenance management system (MMS) remote data entry feasibility study was conducted by North Carolina during 2008. The main objective of this study was to evaluate the feasibility of capturing employee and equipment time, work accomplishment, and work location information on handheld personal data assistant (PDA) devices in the field.

PROJECT SCOPE AND OBJECTIVES

The scope of the study covered two types of PDA devices: (*a*) a small, compact, less expensive PDA, and (*b*) a larger, more rugged device. The study used a specific, commercial off-the-shelf (COTS) application developed by AgileAssets, Inc., for capturing employee and equipment time, work accomplishment, and work location information for use in MMS applications.

This feasibility study was set up to answer the following questions:

- Can PDA devices reasonably be used to collect such data in the field?
- If so, what general type of PDA device would work better, large and rugged or small and compact?
- Can PDAs be integrated with existing MMS applications to download tasks and upload them back into the main system after entering the data?
- Should Global Positioning System (GPS) be used to capture location of jobs in the field?
- Is the existing AgileAssets' PDA application suitable for use with MMS function and what enhancements might be needed?

PROJECT DESCRIPTION

Approach

This project organized a direct seven-step approach to accomplish the objective.

1. Select and buy PDAs and GPS devices. This was the responsibility of the North Carolina Department of Transportation (NCDOT). Nineteen units were purchased: 11 small, inexpensive devices and eight larger, more rugged devices.
2. Install and test. Once the PDA and GPS devices were acquired, the vendor application software was installed on the PDAs and tested. The application software and hardware is described in more detail in subsequent sections.
3. Train the trainer. AgileAssets trained three support teams which were used to do field training. These teams consisted of two people and made up of either MMS support personnel, state road maintenance unit (SRMU) staff, or AgileAssets staff. A 1-day training session was held in Raleigh for these personnel.
4. Field use of Type 1 device for 4 weeks. Three devices were taken out to each of the five participating divisions. The field participants were introduced to the first type of device and given hands-on training. Once trained, the participants used the first device type for all their work for a period of 3 to 4 weeks. A detailed description of the process used by field participants is given below.
5. Field use of Type 2 device for 4 weeks. The field participants then changed to the second type of device. With minimal additional training required, the participants used the second type device for all their work for a period of approximately 3 to 4 weeks.
6. Feedback from trainers and field users. Surveys of the participants' experiences and feedback were conducted by SRMU personnel. Trainers also provided written feedback for the study.
7. Final report. AgileAssets, Inc., and SRMU personnel analyzed the survey results and written feed back to compile a final report.

Field Participants

NCDOT personnel from five divisions participated in the study as follows:

- Division 3 traffic services: three units—paint crew, signal crew, and sign crew;
- Division 2 roadside environmental: three units—spray crew, plant bed crew, and rest area crew;
- Division 5 Granville maintenance: three units—shoulder crew, miscellaneous crew, and patch crew;
- Division 9 Forsyth maintenance: three units—miscellaneous crew and two patch crews; and
- Division 12 Iredell maintenance: three units—miscellaneous crew, ditch crew, and secondary construction crew.

Devices Used

The study was set up to test the use of different types of handheld devices with different configurations of GPS (built-in versus separate devices). Two different PDAs were eventually chosen. One was relatively small, compact, and less expensive; the other was more rugged, larger, and more expensive. Unfortunately, the device with built-in GPS capability was not available and both devices were therefore used with a single type of external GPS receiver connected to the PDA devices using Bluetooth technology.

Operating System

The Microsoft Pocket PC 2003 operating system was used to run the COTS application.

Chargers and Charging

Both PDA devices as well as the GPS device had car chargers and were charged as needed while in the field. The PDA devices could also be charged in the office using the cradle provided.

Active Synch Cradles

Cradles were provided for both PDA devices for downloading and uploading tasks and crew information although in the case of the larger device it was possible to bypass the cradle and use the provided cable directly.

PDA DEVICES

Small PDA Device

The smaller and more versatile device comes equipped with both integrated Wi-Fi and Bluetooth (not used in this study) to enable access to the Internet and e-mail from corporate, home, or Wi-Fi hotspots (such as select airports, hotels, and other public places). It also allows cable-free connections to other devices such as the GPS unit used in this study with Bluetooth wireless technology. It also included enhanced security protection with special software.

Product details include the following.

- Operating System: Microsoft Pocket PC 2003.
- Intel PXA270 520 MHz high-performance processor.
- 128 MB total memory (64 MB ROM and 64 MB SDRAM)—up to 65 MB user available memory including 31 MB iPAQ File Store.
- Included network card: Wireless Ethernet—11 Mbps IEEE802.11b.
- Input method: control pad, stylus, touchscreen.
- Included functions: audio playback, Bluetooth compatibility, calculator, calendar, integrated MP3 player, note pad, scheduler, spreadsheet, video playback, voice recording, web browser, wireless e-mail, wireless Internet, and word processor.
- Included accessories: AC adapter, antenna, docking cradle, microphone, speaker, and stylus.
- Battery type: lithium ion, a removable and rechargeable 1440 mAh battery is standard, and offers uninterrupted power and productivity and a 2880 mAh battery is available for extended usage.
- Interface type: audio–headphone out (1/8-in. mini), audio–microphone in (1/8-in. mini), serial–infrared (IrDA-SIR).
- Power options: AC input, rechargeable battery.
- Slots: compact flash Type II, SDIO card.

Larger PDA Device

The larger, heavier (1 lb.) but more robust device provided a 3.5-in. reflective color LCD screen with frontlight. Data is entered via the touchscreen or via the keyboard. It is moisture-, shock-, drop-, and dust- resistant, and provides sealed port and connector covers. It is wireless ready.

Product details include the following.

- Intel Strong ARM SA-1110 Microprocessor 206MHz, 16KB I-cache, 8KB D-cache.
- 64MB SDRAM, 32MB Flash EPROM.
- Preloaded Microsoft Pocket PC setup and diagnostics software.
- Keyboard and input: 38-key keyboard with backlight, four-direction cursor control button, touchscreen LCD, and stylus.
- Battery: lithium ion rechargeable battery (1400mAH/7.4V). Battery duration is 8 h with the front light on; 24 h with the front light off. Battery recharging time is approximately 3 h.
- AC adapter: AC 100V-240V 50/60Hz, auto-sensing–switching for worldwide power supply.
- Multimedia card–secure digital card x 1 (RAM upgrade).

EXTERNAL GPS DEVICE

The study intended to test PDA devices with built-in GPS receiver. This equipment proved to be unavailable for the chosen PDA devices with the specified operating system. Consequently an external GPS unit was used for both PDA devices and was connected to each device using Bluetooth technology.

Product details include the following.

- Operating system: Microsoft Pocket PC 2002 and Microsoft Windows Mobile 2003.
- NMEA 0183 output protocol.
- GPS receiver accuracy: 10 m.
- Transmitting range: 5 to 10 m depending on environment.
- Average acquisition rate: 38-s warm start, 45-s cold start.
- Reacquisition rate: 0.1 s.
- Power source: 900 mAh rechargeable lithium ion battery (8 h continuous operation time) or AC adapter.

PDA Application Software Description

The PDA application software contains two modules, the offline module and the online module. The offline module is used in the field to record work information. The online module is used in the office to upload and download information to MMS.

The field process involves the following steps.

1. If using scheduled tasks from the main MMS system, create and maintain schedules using the main MMS system.
2. If using scheduled tasks from main MMS system or if crew has changed from previous days, connect the PDA device in the office to the main MMS application through the PDA cradle using Microsoft ActiveSync and download tasks onto the PDA device for the day from the main MMS application. Update shortlists by adding any new employees, equipment, or materials and remove any of these resources that will not be in the field on the selected day.
3. In the field, create additional tasks as needed using the offline module. For each task, assign start and end locations and enter the number of hours worked. If necessary, edit the day cards to reflect an individual's or piece of equipment's actual time if different than the entire field crew.
4. In the office, using the online module, upload to the main MMS system the information recorded in the field.

Key features of the COTS PDA application software used in the study:

- PDA users log on to the PDA and are authenticated by the main MMS software during download–upload;
- A PDA crew composed of specific employees and pieces of equipment can be created on the PDA device and updated as needed;
- Scheduled tasks can be downloaded from the main MMS program;
- Tasks can be created on the PDA in the field;
- Start and end locations of tasks can be stored using both explicit route and mile point or by GPS;
- Durations entered for tasks are automatically applied to the crew thus creating day cards automatically for employees and equipment; and
- Individual day cards can be edited in the field prior to upload.

Field Process Description

A typical workflow is as follows.

1. Create and maintain schedules using the main MMS system.
2. In the office, using the PDA online module to connect to the main MMS application through the PDA cradle using Microsoft ActiveSync.
3. Download onto the PDA any tasks for the day from the main MMS application software. If there are no tasks for the day, create them in the field using the offline module.
4. If necessary, update your short lists by adding any new employees, equipment, or materials, and remove any of these resources that will not be in the field.
5. In the field, create additional tasks as necessary using the offline module, then for each task:
    a. Assign start and end locations using GPS coordinates, or route and mile points;
    b. Enter the number of hours worked; and
    c. If necessary, edit the day cards to reflect an individual's or piece of equipment's actual time if different from the entire field crew.
6. In the office, using the online module, upload to the main MMS system the information recorded in the field.

FINDINGS

General Statistics Based on Data Uploaded to Database

Summary Statistics

This section describes the findings and conclusions of the study and makes recommendations. The following high-level statistics were calculated from the data uploaded from the PDA devices into the main MMS database.

Field personnel successfully uploaded 340 tasks with associated task numbers in the main MMS application. These tasks are used as a base data set for various, more detailed comparisons in subsequent sections of the referenced final report (*1*).

The breakdown of these 340 tasks are

- Original MMS tasks downloaded to PDA and uploaded with valid GPS readings: 144;
- New tasks created on PDA and uploaded with valid GPS readings: 126;
- Total uploaded PDA tasks with valid GPS readings: 270;
- PDA tasks without valid GPS reading: 70; and
- Total PDA tasks with valid MMS task number: 340.

It can be seen that of the total number of tasks with valid GPS readings that were uploaded, roughly half were scheduled in the MMS and downloaded and half were newly created on the PDA in the field (53% and 47% respectively). This shows that users like to be able to both download scheduled MMS tasks as well as create new tasks in the field on the PDA.

Of those (340) that were successfully uploaded, 79% had valid GPS readings. Considering how new this technology was to the field users, this represents a very high percentage that would only improve over time. Nonetheless, because of inevitable problems that occur from time to time with recording GPS data, this figure (21% nonvalid GPS) also shows the importance of being able optionally to record route and mile point information in addition to using GPS.

Tasks per Administrative Unit

Tasks created on the PDA by the participants were distributed fairly evenly across the participating divisions. Thus, the concept seems workable across several units ranging from roadside environmental to maintenance operations. Most divisions were successful in capturing GPS locations 80% to 90% of the time. Division 2 was only able to capture GPS 50% due to the difficulties encountered in using the larger PDA device. It is not possible in the study to conclude whether this was a result of personnel or training problems with the devices or whether it was a technical problem obtaining GPS satellite locking from these locations. This question should be pursued further.

Tasks by Activity

A total of 38 work functions were used, with most tasks created for longline painting and full-depth patching. The 20 most common work functions accounted for 90% of the tasks. It is noteworthy that at least the top 12 functions had high GPS percentages (Table 1).

Day Cards Analysis

Comparisons were made of the day card data uploaded from the PDA devices to try to determine how many of the day cards that were entered into the PDA were different (changed) when entered into the financial management information system (FMIS). This was accomplished by comparing uploaded day cards from the PDA device with approved day cards (that is, day cards that have come in from FMIS that are not editable in MMS).

A high percentage of day cards were returned to MMS through the interface from FMIS even though no automatic interface currently exists to move day cards from MMS to FMIS. This suggests that the PDA day card information either had to be typed into the FR1101 by hand or copied and pasted from the MMS FR1101 Excel reports. Since the information was already so reliably copied into FMIS FR1101 forms, it is concluded that the data was considered to be by the participants valuable enough to be copied and that if an automatic interface were provided to bring the data into the FR1101 forms in FMIS (i.e., as basically an automatic method of completing existing FMIS FR1101 forms so that the information was then subject to all existing checks and balances), these percentages would increase further.

The data analysis shows the following:

TABLE 1 Work Function Findings

Work Function	No. With GPS	No. Without GPS	Total	% With GPS
4101 Longlines painted	43	13	56	77%
3715 Full-depth patch hot mix	28	4	32	88%
3621 Installation–maintenance ersn control device	20	2	22	91%
3771 Major maintenance of ditches	21	1	22	95%
4325 Seeding and mulching	13	8	21	62%
3712 Mechanical patching	15	2	17	88%
3774 Minor maintenance of ditches	15	1	16	94%
3871 Miscellaneous drainage structures	11	5	16	69%
3711 Manual patching	12	2	14	86%
3761 Removal of hazards	10	1	11	91%
4032 Sign maintenance–replacement	9	2	11	82%
3855 Installation of pipe culverts	8	3	11	73%
4331 Planting and plant maintenance	3	6	9	33%
3861 Maintenance of pipe culverts	5	3	8	63%
4326 Ditch protection	2	6	8	25%
3773 Maintenance of high and low shoulders	6	1	7	86%
3851 Installation of drive pipe residential	5	2	7	71%
4055 Sign installation	5	1	6	83%
4142 Traffic signal emergency maintenance	6	0	6	100%
3705 Pavement widening	4	1	5	80%
3717 Milling–grinding asphalt pavement	4	0	4	100%
4321 Roadside vegetation establishment	1	3	4	25%
3605 Clearing and grubbing	2	1	3	67%
4311 Herb use on pavement	3	0	3	100%
3607 Roadway earthwork	2	0	2	100%
3915 Changeable message sign	2	0	2	100%
3785 Back sloping or shoulder widening	2	0	2	100%
3612 Road base construction w/ABC	2	0	2	100%
3765 Litter pickup	2	0	2	100%
3756 Machine clearing of ROW	1	1	2	50%
3766 Bagged litter pickup	2	0	2	100%
3755 Manual clearing of ROW	1	0	1	100%
3762 Clear debris from roadway	1	0	1	100%
4135 Traffic signal initial installation	1	0	1	100%
4137 Traffic signal preventive maintenance	0	1	1	0%
4315 Aquatic weed control	1	0	1	100%
3862 Maintenance of outfall ditches	1	0	1	100%
3763 Remove debris from ROW	1	0	1	100%
	270	70	340	79%

ROW = right of way

- Of the day cards generated on the PDA devices and uploaded as unapproved day cards into MMS, almost 90% of accomplishment day cards and around 80% of labor and equipment day cards were successfully copied to the FMIS FR1101 forms.
- Of these day cards, the vast majority (60% of accomplishment day cards, 74% of labor day cards, and 76% of equipment day cards) were unaltered in FMIS.
- For unknown reasons significantly more of the day cards that were changed in FMIS were increased rather than decreased.

Participants' Responses to the Pilot PDA Project Survey

A written survey was prepared and distributed to the participants in the pilot PDA project. This survey was designed to solicit their perceptions of the hardware and software, and provided a five-point response scale ranging from 1 (easy or strong agreement, depending on question wording) to 5 (hard or strong disagreement, again depending on the question working). Approximately 30 surveys were distributed and 28 surveys were returned. The surveys were then analyzed and the findings from these surveys are summarized in the following sections.

Summary of Responses Regarding the PDA Devices

The participants provided the following feedback in regard to the PDA devices.

- The powering of the PDA devices was not an issue. Powered both from AC outlets and power points in vehicles were effective.
- Most participants were successful in interconnecting the PDA devices with a computer via the cradle and with establishing a logical connection to the MMS database via ActiveSync (2).
- Participants' preferred the smaller PDA device over the larger device.
- Some participants preferred to have a hard case regardless of the PDA brand used; others had no preference.
- Participants generally felt that a keypad was important to have regardless of the PDA brand, although a wide variety of opinions were expressed as summarized in the full report (3).
- Participants clearly preferred a PDA that could easily be carried in a pocket, thus the smaller PDA was preferred to the larger PDA.

The field users made numerous comments about both PDA brands as follows.

- Numerous connection problems with Bluetooth communication were reported. Some problems were physical but most were caused by inadequate training or inexperience with the equipment.
- The devices at times locked up, necessitating soft resets which could cause small amounts of data to be lost.
- Most participants preferred the smaller over the larger because of such things as screen brightness and the awkwardness of the external keypad on the larger device.
- Most participants felt that the PDA and GPS devices should be integrated.

Several conclusions that may be summarized from the survey follows.

- The smaller devices were much preferred over the larger devices. This appears to be because the participants could put the smaller devices in their pocket.
- Opinion on a hard case varied, indicating that this was not a deciding factor in selection of PDA type.
- Opinion on availability of a keyboard varied indicating that this was not a critical factor.
- Devices should not be fixed in the vehicle as some users (Division 3) like to take them out of the vehicle all or most of the time. Other users (Division 3) like to keep the device in their vehicle at all times, thus an optional mounting bracket might be useful.

Summary of Responses Regarding the GPS Device

The study participants provided the following feedback in regard to the GPS device.

1. Most participants found the GPS device easy to use.
2. The participants almost always used the GPS device inside the vehicle.
3. The GPS device was generally successful in acquiring a reasonably accurate location reading.

The field users made the following comments about the GPS device and how that device worked with both PDA brands.

1. May reported connection problems with Bluetooth communication. Some problems were equipment related, but many resulted from trainers not having adequate training or experience.
2. If the GPS device was not properly charged, problems resulted.
3. The PDA devices often needed to be reset due to using the external GPS.
4. GPS reception was a problem is certain areas. For instance, Division 5 Granville maintenance had problems where GPS did not work well in the northern part of the county and they had to walk around with the GPS device held up in the air.
5. Most users felt that the PDA and GPS devices should be in one unit.
6. A technical help desk was requested to diagnose and solve GPS problems over the phone.

The following conclusions derive from the survey.

1. The GPS device was relatively easy to use. In spite of individual problems encountered, most respondents were able to get a GPS reading most of the time.
2. Some field crews had more trouble than others. For example, Division 12 almost always got GPS readings, but Division 2 got readings less often. This finding is confirmed by the uploaded data.
3. Some users preferred to take the GPS device out of their vehicle (Division 5 crew), or needed to, to improve reception. Some users never did (Division 3 users).
4. The ease with which users were able to obtain beginning and ending mile points from the map was more widely distributed. This aspect is discussed in more detail in the section on Accuracy in Capturing Locations Via a GPS Device.
5. Survey results show that it was possible to use the separate Bluetooth–GPS device successfully. However, better training is needed.

Summary of Responses Regarding the Software Used with the PDA Devices

The participants evaluated the custom software program used on PDA devices as follows:

1. The majority of participants found it easy to download tasks.
2. Nearly all participants found it easy to set up a crew for the day's activities.
3. The majority of participants found it easy to upload tasks, although a significant number of difficulties were reported.
4. Most participants easily recorded information about tasks on their PDAs but some had trouble.
5. Recording day card information was easy for nearly all participants.
6. Field personnel commented that finding starting, and ending mile points was difficult at times because neither route nor mile points were shown on the map, especially for short roads in subdivisions. This problem is outside the use of PDA.

Summary of Responses Regarding Training

This was a proof-of-concept study and some participants felt inadequately trained. Of course, now that the "bugs" in the hardware and software have been largely resolved, a more thorough and accurate training program can be developed and employed for future deployments.

Accuracy in Capturing Locations via a GPS Device

The basic concept for location capturing using GPS is to have users record a GPS location at the beginning or end of a task. Because GPS coordinates are not inherently understandable to the average user, the idea would then be to translate these coordinates to a linear reference in terms of route and mile point for use in reporting and for production of maps (where the tasks are portrayed as linear events along the roadway). The translation could be performed in various ways but since the GIS department is the master of the linear referencing system (LRS), one method would be to have this translation performed with custom software provided by the GIS department.

As part of the study, the GPS (coordinate) points collected in the field were post-processed by the GIS department to translate these into LRS (route–mile point) points. This post-processing translation consisted of a simple search to find the nearest route–mile point on the nearest state-maintained route compared to the field captured GPS point. The expected problems were that, depending on the accuracy of both the GPS reading and the maps used by GIS to find the nearest route–mile point, the wrong route would be found. This could happen quite often if the start or end point of a task was located at an intersection. It might happen less often that a nearby route would be selected up rather than the actual intended route. In order to try to detect these problems, study participants were asked to enter the intended route and mile point values into the PDA device as well as capture a GPS reading.

The following statistics are based on analysis of the GPS from and to points uploaded from the PDA devices and the calculated nearest road centerline points:

1. Approximately 95% are within 50 ft of a state-maintained road centerline.
2. Approximately 80% are within 10 ft of a state-maintained road centerline.
3. The calculated start or end route matches the PDA route at least 93% of the time.
4. Approximately 25% of the time, the route calculated from the GPS start and end points are different from one another. This is probably mainly because often the start or end is at an intersection and so the closest match is the intersecting road.
5. In about 40% of cases the PDA start and end readings are within 0.5 mi of the calculated start–end. This probably reflects inaccurate map reading–maps.

Findings

The following findings may be drawn from these statistics.

1. The GPS points recorded on the PDA are generally accurate since 95% of points are within 50 ft of a state-maintained road, and 80% are within 10 ft. The accuracy of pinpointing a point on the ground using GPS, assuming a GPS reading can be captured, seems reasonable.
2. It appears participants already knew route names or were reading their maps accurately with regard to route location of the work. The entries matched the correct GIS routes for work location 93% of the time.
3. It is likely that one or the other point is inaccurately mapped about 25% of the time since cases where points fall at road intersections and are mapped to the wrong route are probably well modeled by detecting cases where the calculated start and end routes are different from one another. Since this occurred, a considerable portion of the time, a more sophisticated algorithm for calculating the route and mile point might be needed.
4. It appears that participants either had considerable problems reading mile points from their PDF-format maps or the maps were inaccurate because in only 40% of cases was the recorded mile point within 0.5 mi of the calculated one. This needs further investigation.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

1. With a total of 15 PDA devices being used in the field for a total of between 5 and 8 weeks by five field units (for a total of almost 100 PDA weeks of use), no PDA devices were damaged or lost.
2. While there were a number of problems initially, the general feeling among both participants and the support crew was that this would increase the likelihood of obtaining more data as well as more accurate data and was the way to go in the future.
3. An interface from MMS to FMIS is not critical based on the fact that so many day cards (over 2,000 of them) were copied or manually re-entered into the FMIS FR1101 forms. Still a method of querying the uploaded data and using it to populate the FR1101 forms (after which the information would be subject to the normal checks and approvals) would be well received and would save a lot of time.
4. Two types of device were tested. The smaller was preferred by far over the heavier, more rugged device. The main reasons given for this were its portability and ability to fit in a pocket.

5. Use of a separate GPS device may have some advantages in terms of obsolescence and replacement, but the additional learning and trouble in using Bluetooth communications caused delays among field users in getting familiar with the systems and ongoing connection problems.

6. The study showed that it is possible to translate GPS points to LRS points with minimal effort and with a reasonable level of consistency and reliability. In spite of both the concept and the technology being new to the participants, GPS readings were still obtained in approximately 80% of cases.

7. GPS readings were obtained 80% of the time and these points had high ground accuracy with 95 % of points falling within 50 ft of a mapped road centerline. After many reported early problems, a large majority of the participants found the GPS devices easy to use overall.

8. Ambiguous translation of the GPS point to LRS occurred about 25% of the time. Many of these instances occurred at intersections.

9. Using GPS is considerably more accurate than entering locations as LRS route–mile point locations based on reading from a map because although 93% of the time the participants entered the right route, only 40% of the time were the entered and calculated mile points adequately close.

10. Roughly half of the total number of tasks with valid GPS readings uploaded, were scheduled in MMS and downloaded and half were newly created on the PDA (53% and 47%, respectively). Thus both MMS task scheduling information and the ability to create new tasks on the PDA device and successfully upload these to the main MMS system will be important.

11. Almost 90% of accomplishment day cards and 80% of labor and equipment day cards were successfully uploaded and copied to the FMIS FR1101 forms, and of these between 60% and 76% were completely unaltered. This confirms that FR1101 accomplishment, labor, and equipment data applicable to MMS tasks can be captured on PDA devices.

12. All participants were able to download, create, and upload significant numbers of tasks and day cards showing that the concept is technically feasible across a wide range of typical usage by NCDOT field units.

Recommendations

1. Handheld devices should be used in the field for capturing tasks and time information since this is not only possible but welcomed by field personnel.

2. While it was shown that the smaller handheld device was much preferred, it is recommended that agencies not necessarily focus on a single brand of PDA but rather allow the possibility of having multiple devices in the field at any one time so long as the basic architecture and operating system can support the application, possibly allowing a choice by field personnel.

3. Having GPS receivers built-in to the handheld devices could mitigate the startup problems of having separate Bluetooth devices as were used in the study.

4. Since roughly half the tasks uploaded from the PDA were initially scheduled in MMS, it is recommended that the capability of downloading tasks from MMS be retained as well as the ability to create new tasks.

5. GPS should be used to locate beginning and end points on tasks since this appears to be a considerably more accurately method than estimating locations from a map.

6. The ability to enter route and mile point data by hand should be retained for use in cases where GPS readings are not attainable.

7. Users should enter at least the route number in cases where the GPS reading is taken at an intersection so that this information can be used to reconcile ambiguous route detection.

8. While an interface from MMS to FMIS was not deemed to be vital, it is recommended that a method of querying the uploaded data and using this to populate the FR1101 forms should be investigated (after which the information would be subject to the normal checks and approvals).

Limitations

Like any small study these results and recommendations are subject to some limitations as follows.

1. The PDA cannot currently edit shortlists for crews or activities.
2. It cannot be used to identify with supervisor was assigned the task originally.
3. It does not know which data has been uploaded and which was original MMS task data being overwritten.
4. The tests did not actually test integrated PDA–GPS although such integration seems clearly preferable.
5. The study has not yet been validated with a second round of verification tests.

None of these limitations are debilitating and it is recommended the field use of PDAs proceed with additional training and enhancements.

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Maximizing Resource Use to Meet the Maintenance Management Challenge

As Demonstrated by Traffic Signal Maintenance Management in the City of Norfolk, Virginia

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Public agencies are required to maintain and improve the level of service for a continually growing catalog of assets with a stagnant or decreasing number of resources. The need for a comprehensive strategy for maintenance management programs increases along with this growth. The City of Norfolk's Division of Transportation (DOT) has chosen to analyze, improve and document the following six elements of a successful maintenance management system: (*a*) preventive maintenance, (*b*) stock and procurement, (*c*) work tracking, (*d*) workforce development, (*e*) statistical analysis, and (*f*) performance measures in order to make the best use of existing resources and justify requests for additional or alternative resources. The experience of Norfolk's DOT in implementing and improving maintenance management programs and policies has shown that significant gains may be achieved by an agency. The six elements, supporting maintenance programs and policies increase resource performance (efficiency), align the correct resource to the task (effectiveness) and if justified provide rational data to justify an expansion of resources to improve levels-of-service and meet increasing demands of scale. This paper will define each of these six elements, detail its components and explain their overall importance to a successful maintenance system. The synchronicity of each element with other elements of the maintenance management program will also be discussed. Examples of the programs and policies that Norfolk has created or expanded to exploit each element will be provided. Finally the results of the implementation of these programs and policies will be discussed along with a discussion of the lessons learned and some of the problems associated with implementing a maintenance management.

For many public agencies today, the number of signal system assets, the asset varieties and the sophistication of these assets and their related equipments continue to increase. Agency resources, however, have not kept pace with increases in scale and service. How are agencies to maintain or increase their level of service (LOS) to the public in this environment?

The Norfolk, Virginia, Division of Transportation (DOT) is no different. Its resources to maintain assets have remained static while the scale and scope have been stepping up. But the DOT has shown that by implementing and improving maintenance management programs that significant gains may be achieved by an agency. These programs and policies increase resource performance (efficiency), align the correct resource to the task (effectiveness), and, if justified by analysis, provide rational data to justify an expansion of resources to improve LOS and meet increasing demands of scale.

For the purposes of discussion the maintenance management system (MMS) is sectioned into six elements. Each element will be defined and its component parts, policies, and programs discussed in more detail. Particular emphasis will be placed on how the MMS elements were created or improved by Norfolk. Finally a treatment of the lessons learned and some of the problems associated with implementing maintenance management will be discussed.

BACKGROUND

Norfolk is Virginia's largest city during the work day and the second largest after hours with some 239,000 residents. It is the cultural, educational, business, and medical center for the 1.7 million inhabitants of the Hampton Roads metro area in southeastern Virginia. Norfolk hosts the region's international airport, one of the busiest shipping ports on the East Coast, and the world's largest naval base.

The City of Norfolk's DOT is divided into two functions and locations: traffic engineering and traffic operations. DOT's traffic engineering office is located in city hall downtown. The 21 employees located there consist of engineers, contract managers, and inspectors. Norfolk's Smart Traffic Center (STC) is located in city hall as well. Three operators and a managing engineer work there.

The remaining 25 employees are located at the traffic operations center (TOC) in an industrial park on the outskirts of the city. Ten technicians with a supervisor manage the maintenance of traffic signals. The TOC maintains its own warehouse for sign and signal parts separate from the city's warehouse–stock system. A listing of the assets that DOT is responsible for is found in Table 1.

The maintenance programs accomplished by TOC may be divided into six parts or elements for the sake of convenience.

THE SIX ELEMENTS

This paper discusses six important programs used by Norfolk's DOT for effective maintenance management. Not every organization need employ every program, while others may choose to use others in addition to these. The first of the six and the foundation upon which all the others will be built is preventive maintenance (PM). PM is the proactive approach to maintenance—fixing things before they break. The stock and procurement program handles the ancillary inventory, purchasing, and stock tasks. The work order system is the data-gathering center. This program must collect all the data, surveys, and other information necessary for creating the performance measures. The workforce development program is instituted to ensure that personnel have the knowledge to complete their tasks. The statistical analysis program

TABLE 1 Traffic Signal System Assets

	Traffic Signal System Assets	**Quantities**
1	Signalized intersections	284 intersections
2	Flashing school zone signs, warning, and beacon signs	98 locations
3	Fiberoptic cable on the signal system communications network	103 mi of cable
4	Closed-circuit television cameras	20 locations
5	Dynamic message signs	4 units
6	Communication devices	384 units

gathers and aligns data for analysis and use in the decision-making process. Finally, a PM program reports the measures and indexes used to manage the maintenance operation.

Even the smallest agency will be familiar with the concepts represented as the elements of maintenance management, though they may use different terminology or have implemented the programs differently. The elements and their supporting programs and policies are certainly not limited in application to transportation but appear in any field where reliability of an asset's function is necessary.

PREVENTIVE MAINTENANCE

PM is managed maintenance. Work done before an asset or equipment fails (to prevent that failure). That work can be anything from cleaning graffiti from the exterior to a wholesale replacement of the unit. The goal of PM is only partly preservation of the asset itself. The prime goal of PM must be to preserve the operation of the asset or component. The entire reason for the assets existence is to make possible some function or operation. While each asset has a built-in dollar value in of itself, the function is why it is there. The trick is to determine what and how much work is relevant to keep the asset or part of the asset functioning.

Norfolk's DOT maintenance management program makes preventative or scheduled maintenance the highest priority. If more than 20% of the workforce's time consists in responding to service calls, the maintenance is not being managed and a dangerous downward slide toward larger number of reactive calls and less-managed maintenance is indicated. That PM programs pay for itself is no longer in much doubt but must not be taken for granted. The cost of PM in the amount of resources delegated for implementation must be weighed against reduced unscheduled response and repair. Norfolk has had a significant reduction in responsive calls since beginning its PM program. There is a direct relationship between PM and reactive maintenance. Directing resources toward PM reduces the resources required for reactive maintenance.

PM Program Types

Tighten, Lubricate, and Clean Programs

PM as defined in this paper consists of several components or concepts. Tighten, lubricate, and clean (TLC) is probably the most familiar definition of PM to most in this industry. Many early studies seemed to indicate that PM (perhaps better defined as TLC PM for these studies) failed to show any effect on decreasing the downtimes of traffic signal equipment. These studies may have been used to demonstrate that PM is ineffective. They may in fact better illustrate that TLC is only a portion of a good PM program.

Replacement Programs

Replacement programs are a more proactive form of reactive maintenance, basically replacing an asset or part of an asset before it fails. This is one of the most popular maintenance methods (whether recognized or not) in the transportation world, probably because it occurs more or less naturally as part of a technology change or upgrade. In Norfolk the movement to replace incandescent lamps with light-emitting diodes (LEDs) has had the more or less unintended effect of also replacing signal heads and head-mounting structures that badly needed replacement. Until the late 1990s this was DOT's only PM program.

Predictive Maintenance

"Predictive Maintenance is a maintenance activity that predicts and suggests actions to be taken to extend the life of the unit. A predictive maintenance check does not in of itself extend life" (*1*). Predictive maintenance (PdM) is a concept not often used in the traffic signal world but that should be familiar from daily life. Most people not only service their automobile regularly but also monitor their engine temperature and oil pressure as well. PdM programs can be as simple as that.

For DOT, there are two forms of PdM. The first form of PdM is those checks or measurements that are taken as part of specific PM work. The checks made to the neutral terminations of traffic signal field indications for electrical back feed voltages are good examples of checks made to suggest actions to perform but that do not correct failures themselves. The second example can be defined as operational. Traffic signal systems enable technicians or STC operators to monitor systems and system reports for predictive signs of decreasing LOS and asset failures. Norfolk DOT technicians analyze daily system error log reports for asset failure symptoms and patterns. STC operators stand watch over central display screens and are the first to view system alarms and detect decreases in LOS.

Conditioned-Based Maintenance

A close cousin of PdM is condition monitoring or conditioned-based maintenance (CBM). PM checklists contain checks that require a technician to measure the physical condition of an asset or a specific aspect of an asset. Like PdM this check is not in of itself an improvement to the operation of the asset, but a substandard condition will suggest an action that may be taken to prevent a future failure. An entire PM program may be based on CBM such that asset or equipment condition is taken as the base for PM. Norfolk, for example, is more likely to replace traffic signal heads by condition rather than life cycle. The lifespan of traffic signal heads near the salt water of the Chesapeake Bay are remarkably reduced when compared with those in farther locations.

DOT uses a combination of these types for its PM. The daily PM check of the signal system's error logs and operational reports by technicians is PdM. Technicians use the system like an automobile's dashboard of gauges to look for typical patterns and deviations from these expected patterns that may act as a predictor of future failures. The semiannual and annual PM checks at the intersection include TLC tasks along with CBM that may involve replacement of infrastructure components or equipment depending on the conditional assessment performed by the technician.

Reactive Maintenance

Reactive maintenance is the opposite of preventive maintenance. Whatever the term—reactive maintenance, unscheduled maintenance, emergency repair, or fire fighting—this is what is being avoided. Though, heroic and somewhat addictive to technicians, this is no way to run a maintenance shop or maintain an asset. It may make sense in some cases to wait for something to break before fixing it but in the instance of operating traffic signals, and for the purposes of this paper, it will be assumed that uptime is desirable.

There is an external cost to reactive maintenance, not as easily quantified as others costs may be. Less measurable are losses in morale and work ethic. Never planning, always reacting, being continually in a position of catching up, is extremely stressful. There may be a feeling of euphoria in diving in and solving problems while traffic piles up in queue and the police stand in the street but the stress is undeniable and the let-down unavoidable. Reactive staffs have a wait-and-see attitude in general. They are busy waiting (unproductively) for the next disaster rather than analyzing the last failure or improving the system to avoid future examples of the last one. They are resting up for the next all nighter.

Norfolk's DOT has not reached its goal of less than 20% reactive maintenance at the time of this writing and its resolve will be severely tested by the recent financial crunch in agency funding.

Planning and Scheduling

PM is scheduled maintenance. Scheduling is more important for PM than any other type of maintenance. Checks must be performed when scheduled or the entire purpose of PM is defeated. Schedule drift is a common problem for PM planning. The PM planner schedules a check on a certain date. For some completely valid reason, usually reactive maintenance, a check must be deferred to the following week. Over a period of time it is possible to observe that this check and other related checks drift a little farther from the original date each year. This drift can negatively affect the entire PM schedule.

Norfolk as part of its efforts to increase scheduled maintenance is in the process of adding infrastructure beyond signalized intersections to its PM program. Adding warning lights, pedestrian crossings, school zone flashing signs, as well as intelligent transportation system (ITS) devices will involve the addition of more than 200 new PM checks to the system.

STOCK AND PROCUREMENT

Figures from industrial maintenance indicate that 40% to 70% of maintenance budgets go to fund parts and materials (*2*). Stock and procurement issues rank second only to preventive scheduled maintenance in importance to an effective maintenance management program.

The fundamentals of stock management are deceptively simple. Spare parts and material are required to repair equipment, replace infrastructure, and maintain operations. It is necessary to decide what must be kept on hand and what can be ordered later depending on how critical the part is to the operation of the asset and on how critical the asset is to the LOS provided to the public. As the parts kept on hand are used, more must be purchased so that the correct amount of spare parts, material, and stock are kept in inventory and available to maintain LOS objectives. Inventory is a balancing act. The size and depth of the stock inventory must be balanced against the downtime caused by a wait for parts. Norfolk balances its LOS to citizens and motorists against the inventory carrying cost.

Maintenance Inventory Control

Controlling the amount of spare equipment that is stocked while maintaining a supply of necessary items is important, Norfolk has a centralized inventory control system where parts and equipment are housed in a central location and are requested from this location on an as-needed basis. The staff at the central location maintains the inventory records on the computerized MMS (CMMS). Inventory discipline is necessary to make the system work. The computerized part system must be used to reorder parts and track them (order transaction) and parts and material must be checked out (issue transaction). The storage shelves must be well organized and someone must receive parts (receive transaction) into the system and if a part is not used it must be checked back in (adjustment transaction).

Norfolk DOT's computerized stock inventory system includes transaction tracking of all receiving, issuing, and adjusting the parts inventory accordingly. Work order tracking include a parts and materials link to the asset the work is assigned to. Built-in inventory reports feature part inventory, parts to reorder lists, and part inactivity tracking. Part supplier information in the system includes manufacturer, vendor, and warranty information. The inventory location information section of the system designates the exact bin, shelf, and building for each part.

Gains Made Through DOT Improvements

Projects are no longer kept waiting on materials. Keeping an inventory of critical parts and a careful count of transactions ensures that the parts are on hand for upcoming jobs. Planning and scheduling allows the ear-marking of parts and materials for upcoming projects through the work maintenance system.

The time required identifying materials has been reduced. Norfolk's well-organized warehouse has each part bin labeled, barcoded, and stored in the computerized part inventory system. The bins are also organized such that asset categories like traffic signal head-mounting parts are grouped together. This structure also reduces the time required finding substitute materials as related equipment–parts are grouped together and easily identified.

The time to prepare and process a purchase order has been reduced. Parts and materials are purchased first and approved through the system second. Purchasing price agreements speed this practice. The CMMS planning–scheduling process allows for more latitude to process part and stock purchases.

WORK MANAGEMENT SYSTEM

This is the process of recording, tracking and maintaining all maintenance activity data. The work management system is used to track the process from the original service request, to planning, scheduling, and acquiring work performance figures. Failure and root cause data may be recorded and tracked as well. A CMMS is best implemented by the organization to simply the discipline and routine collection of this data. Without this collection, analysis, failure forecasting, and much of the benefits of a proactive maintenance system will be impossible to acquire. Most of the data needed by the various maintenance processes is collected at this stage and the relationships between the processes cannot be established if they are not tabled in a closely controlled fashion.

The relationship between asset and work management may be created within the CMMS as well. Service requests and work orders may be linked to the assets they were created for. In this way, records of parts usage, asset life-cycle costs, and asset failure patterns are created and maintained.

Planning and Scheduling

Work management is truly defined by planning and scheduling. Planning and scheduling are the tools used to manipulate the work to make it manageable. It is not possible to reach the 80% scheduled maintenance goal without planning. Norfolk has aggressively made use of the CMMS's planning and scheduling tools.

At DOT, when work is requested by a customer, a project is authorized, or a PM checklist deficiency is discovered, a CMMS service request form is created to record all available information. The request is also assigned to a specific work planner–inspector. The planner is responsible for planning and scheduling the work to complete the request. The planner uses the CMMS to evaluate the availability of resources including technicians, vehicles, and parts and with the information schedules and assigns these resources for the work. The planner is also responsible for follow up. He or she must review their estimate of time, quantities, and costs for accuracy and reschedule incomplete work. The planner is not restricted to in-house resources but may use contracted resources if available.

Contracting Maintenance

DOT has largely switched larger construction operations (like pole installation) to its contracted workforce. Large, predictable scheduled maintenance projects have also been provided to contractors. The transfer of inductive loop installation, LED signal-head replacement and the installation and repair of underground conduit has proven to be more cost effective when accomplished using the city's indefinite quantities (IDQ) contractor; more information regarding the IDQ follows in the implementation section. DOT has secured funding for and is in the process of creating a PM IDQ to alleviate the upcoming increase in the scale and scope of PM checks for new asset types.

WORKFORCE DEVELOPMENT

How often is maintenance a return to a location where the failures were supposedly corrected? Small differences in technician skills can either decrease or increase the failures caused by maintenance. Consider the wide range of knowledge, skills and experience present in any agencies' technicians. If an agencies' workforce is highly skilled and knowledgeable and they are assigned only to projects they are qualified to perform, the number of technicians can be reduced. Service requests will be reduced as work will be performed correctly the first time.

Staffing Levels

Beyond the simplest determinants of providing a given number of maintenance technicians per asset, several factors should be considered when determining staffing levels. The scope of work covers the breadth and depth of job performance requirements. This range may be from extremely narrow, single-task, repetitive job tasks to broad, multiskilled jobs. Equipment reliability should be considered. Highly reliable assets and equipment can be managed with relatively fewer maintenance technicians than comparable unreliable assets. Historical information must be reviewed. An analysis of comprehensive maintenance work order information often reveals that most of the root causes of the perceived maintenance problems with the plant and equipment are outside the direct control of the maintenance staff.

There is growing concern that today's workforce does not have the skills and knowledge necessary to keep pace with the ever advancing technological complexity of equipment they are required to maintain. The scarcity of vocational–technical school and apprenticeship schools does not bode well for the industry at large. Agencies must therefore develop their own skills-based technical training programs for their specific equipment and assets. With this in mind, DOT's efforts have concentrating on in-house on-the-job training (OJT) and the DOT Career Ladder program.

Career Ladder

Norfolk DOT has created a Career Ladder program for traffic signal maintenance technicians to provide guidance and the opportunity for merit-based advancement. If team members can demonstrate that they have the skills, experience, and maturity of the next level of technician they will be automatically reclassified to the next higher job level. DOT has created four job skill levels of traffic signal technician (I through IV with IV being the most skilled level). To ensure the integrity of the program, specific documentation of the team member's achievement must take place.

On-the-Job Training

OJT booklets for each skill level were created with the representative skills required to master each level. Each skill contains specific step-by-step tasks that skill experts use to ensure that the skill can be competently completed by the candidate for advancement. The experts must sign and date each task making themselves accountable that the candidate can be trusted to independently exercise each skill. The OJT experts are chosen by the traffic maintenance supervisor from traffic signal team members past and present. Regular OJT training with an emphasis on the skills and tasks within the OJT booklet is provided weekly to groups of five or less. An example of the OJT booklet may be found in Figure 1.

International Municipal Signal Association Certification

The International Municipal Signal Association (IMSA) certification requirements for advancement provide an independent standard at each level on the ladder. IMSA certifications are the accepted standard for public safety personnel throughout the United States and Canada. Nearly 100,000 certifications have been administered by IMSA since its beginnings in 1898. This standard also commits Norfolk to providing the program to personnel on a regular basis.

A

IV

III

A104 –Cabinet Testing; *Required for: TST3, TST4,*

OBSERVATION OF PROCESS			
#	TASK	YES	NO
1	Prep Work Area		
2	Insert Isolator		
3	Insert Detection		
4	Insert Flasher		
5	Insert Load relay		
6	Install 170 Controller with test Program		
7	Insert Monitor With test PC card		
8	Connect Cabinet Display Monitor		
9	Connect Electrical Service		
10	Bring To Operation		
11	Verify All Input And Output are Tested		
12	Allow Burn In Time		
13	Secure For Installation		

TOOLS / EQUIPMENT			
Correctly used the following tools and equipment			
#	Tool/Equipment	YES	NO
1	Common Hand Tools		

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SAFETY			
Followed these safety procedures;			
#	Procedure	YES	NO
1	MUTCD		
2	IMSA		
3	NEC		
4	NESC		
5			

INSPECTION OF WORK			
#	Inspection	YES	NO
1	Clear area		
2			
3			
4			
5			

Task Performance Score 5 4 3 2 1
Optional: Circle one above
5 = Extremely skilled, 4 = Above average
3 = Average, 2 = Below average, 1 Unskilled
Date Task Successfully Completed:
Supervisor's Name:
Title:
Supervisor's Signature:

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FIGURE 1 OJT booklet task performance inspection pages.

Employee's Performance Evaluation

The employee's performance evaluation receives new emphasis with the career ladder. The periodicity of the evaluation was doubled from an annual evaluation to an annual and semiannual evaluation. While the semiannual does not carry the same weight as the annual, it does provide the supervisor with the opportunity to make sure the candidate is aware of where he stands. Also the technician is to be employed in each level for 1 year before becoming reclassified to the next level. DOT has reclassified two individuals at TOC since the inception of the career ladder program out of the 10 who are eligible.

Cross-Training

Norfolk has limited funding for outsourced training but some of the most experienced and knowledgeable technicians are employed in the region. To take advantage of this resource, DOT created its cross-training program. These seasoned technicians while not necessarily experienced as instructors can certainly show less-experienced technicians techniques and methods to strengthen their competencies in areas they may be less familiar with. Norfolk enforces a scheduled rotation of team members. All maintenance functions are accomplished by two-technician teams when possible. Each technician rotates to a different team each month. The more knowledge and skills are increased for the entire maintenance group, the less the rework maintenance for the group and the seasoned technician.

Recruiting

DOT has a policy of advertising in local papers, on the Internet, and in the *IMSA Journal* and website. Recently, DOT has marketed its career ladder program to both the external workforce in the local area through job fairs and vocational events and internally to workers in other city departments. The need for workforce development, its effectiveness in decreasing rework trips, and its outcome of increasing maintenance efficiency can be demonstrated by statistical analysis.

STATISICAL ANALYSIS

Statistical analysis puts together all the data gathered around a particular asset or resource. The information associated with downtime, emergency repair, repair stocks, maintenance costs, and the labor, equipment, and part resources information is collected and decisions are made based on this information. The economics, efficiency, and effectiveness of the operation is measured and indicated. With accurate data an agency can determine whether to continue to maintain or replace an asset. It can determine which parts to stock and which to order just-in-time. An agency can also make an accurate assessment of whether it is more cost effective to use contract labor in place of its own. The data gathered by the previous programs is vital to make relevant decisions. All the system baseline data must be collected and analyzed. The performance measures for each element are analyzed and indexed.

PM Analysis

Norfolk creates charts and maps of signal malfunctions and failure rates by location and equipment type from work management system records. The CMMS also creates component failure rate reports and the mean time between failures index by component type–model and age category. The system compiles tables of failure rates by failure codes indicating the failure type. The mean time to repair (MTTR) for different types and models of signal components are created by the CMMS as well.

Adherence to PM schedule completion and periodicity is analyzed through the CMMS. Analyzing conditional data collected by PM inspection checks determines what parts and equipment should be replaced before failures occur.

Stock Inventory Analysis

Parts consume 40% to 70% of every maintenance dollar (*2*). Analysis of part usage can be key to maintenance control. By identifying statistically the highest use parts and their relative costs DOT has invested its improvement efforts on these areas of highest return. Pareto and root cause analysis are applied to reduce the incidence of these failures such that not only is there considerable savings in material costs and inventory but also in the labor and associated equipment costs previously expended on these failures. Analysis is also applied in reviewing part specifications and past failure and maintenance requirements history, responsiveness of vendors and manufacturers in meeting supply requirements, and the total in-house processing time from the technicians request for a part to its issue.

Work Management Analysis

Analysis is conducted through the CMMS to ensure that all labor, parts, and equipment recorded for TOC has been accounted for properly on a regularly scheduled basis. Work order activity analysis is conducted to determine the accuracy of technician reporting and job completion. DOT planners monitor their estimates against the actual time taken to complete and the associated costs for accuracy, revising future estimates if necessary.

Workforce Development Analysis

The MTTR index is created by the CMMS, as well for different types of repair (e.g., by type or level of expertise required), to identify where staff resources need to be supplemented. Career ladder step development is closely monitored by supervisors and the OJT booklet task lists are frequently revised for accuracy and validity.

Asset Management Analysis

High-level analysis takes place here in the asset management decision-making process. What assets should be added? What assets can be removed? What assets should be replaced? The actual LOS supported must be compared with the LOS goals and objectives and based on what is determined by the collected data and analysis, decisions as to what programs to fund and at what level they should be made.

Performance Measures Analysis

Statistical analysis of performance measures should answer questions about the measures. Are the measures accurate? Are the measures naturally linked together in such a way that changes in measures at the base level are reflected by measures at the top?

PERFORMANCE MEASURES

Performance measures should be developed in such a way that they can be used to point to problems before they happen. They should be designed to feed the idea of continuous improvement. They should be used to forecast change, show opportunities to improve processes and shine a light on problems before they happen. Most systems for measuring performance are developed in a tiered system with a top-down approach. When the strategic indicators at the highest level indicate a problem, it should be possible to query those below to find the source of the problem since the higher measures are built upon the base of those below them.

Strategic Indicators

At the highest level are the strategic indicators. The measures are used to test the success of the agencies strategic plans. All the lower measures build to this point so that the agency can judge if its goals and objectives are being met and to tell if it's customer is pleased with the performance. The traffic operations and management group—in which are included asset maintenance functions—may have as its strategic plan to decrease delay, increase volume and flow etc. As quantitative measures it may use the classic and specific measures provided by traffic engineering such as volume over capacity, LOS for key areas, cumulative hours of delay, etc. It would be advisable to further quantify these figures by adding the costs associated with providing the measures. This makes it easier for the public to make a qualitative decision regarding the worth of the particular operation.

Financial Indicators

The next tier down consists of financial measures. These measures are the costs and benefits provided by the agency. They consist of those financial measures that impact the strategic measures of the tier above. Examples of financial indicators for a particular maintenance process or department would be the average cost of replacing, upgrading and rehabbing per signalized intersection. The total cost per asset can also be compared against the cost of each maintenance employee required to maintain a particular asset. Material cost should be considered as well. How much material and how many replacement parts must be warehoused and what are its present value and its replacement value? Lastly what roles do costs associated with contract labor and materials play against total maintenance costs?

Efficiency and Effectiveness Indicators

The next set of measures is the efficiency and effectiveness of the organization and they understandably impact the financial layer above. An efficiency measure would therefore compare the quantity of output provided against the input used. What this measure does not do however is judge whether the task was necessary in the first place. This is where the customer's qualitative viewpoint comes in.

A common misunderstanding regarding efficiency and effectiveness measures involves reporting only input measures of the group or process. Recording how many traffic signal heads are installed is an example. Counting the total quantity of vehicle detection loops repaired is another example of an input measure without reference. These indicators may the agency's workload but they do not reflect its output measures (effectiveness). A measure of effectiveness and efficiency would be "the percentage of maintenance personnel per dollar of asset value." This is an index that relates the quantity of people to the value of an asset. This metric establishes a relationship between staffing and asset value. Not only is this easier to understand and communicate to others, it is easier to benchmark against ones own program and outside agencies.

IMPLEMENTATION

May 1, 2001, is a good starting point to begin a history of MMS implementation. On that date, the City of Norfolk accepted new infrastructure and a reorganizing of operations functions as part of the Advanced Traffic Management Systems (ATMS) Phase II Project. ATMS Phase II was the implementation phase of Norfolk's vision for an ITS. While many elements of MMS programs had been adopted over proceeding years (including a CMMS in 1993 that was abandoned little more than 3 years later), the increases in the scale and scope of infrastructure, equipment, and related maintenance without a corresponding increase in resources demanded a new commitment to MMS principles (Figure 2).

Prior to 2001, DOT's maintenance was almost wholly reactive. A single three-technician PM team spent the entire year together completing aerial and ground PM checks to schedule. Only one-half of the city's signalized intersections were inspected per year. This meant that conflict monitors and other critical control equipment were tested every other year. Only signalized intersections where included as assets. School lights, beacons, warning signs, etc., were not on any PM list. These assets were in many cases not even inventoried. This PM program was the first PM program implemented by traffic operations and it had only been implemented since 1995. PM did not rate very high as a priority for management at this time. Technicians were frequently pulled from the PM team to answer reactive maintenance needs.

While the addition of the ATMS did release the signal maintenance technicians from much of their controller programming duties, the additional infrastructure and the unfamiliarity with the new system far outweighed any time gains. The interconnect upgrade to fiberoptic cable accomplished by the ATMS project is an example of a false maintenance gain in that the earlier copper interconnect had been abandoned. Installing the new cable was a maintenance increase.

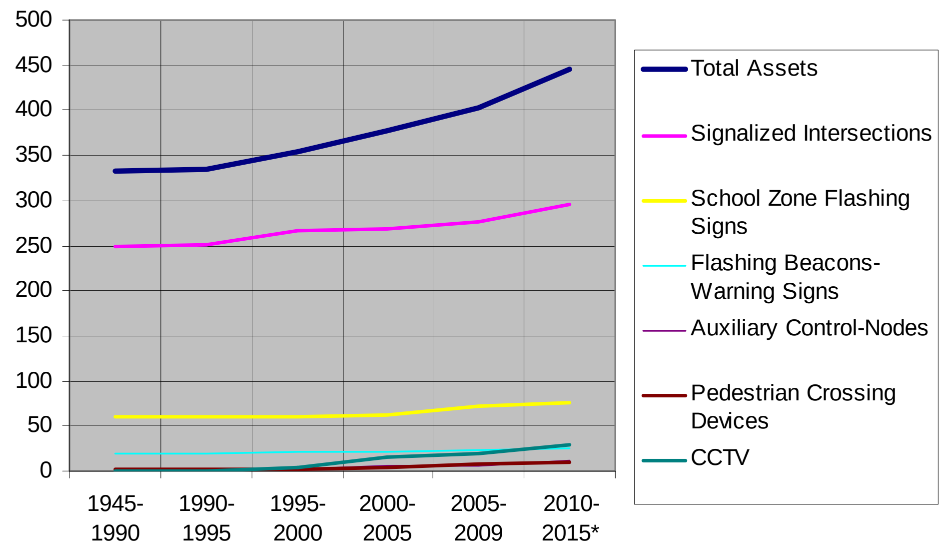

FIGURE 2 Asset growth over time.

With the ATMS many new ITS assets like closed-circuit television (CCTV) and dynamic message signs (DMS) were added. These devices increased reactive maintenance. CCTV, DMS, and communications assets were not included in the formal PM structure. School zone signs, warning and hazard beacons along with pedestrian crossing assets are not scheduled either. Norfolk began scheduling these checks this year. Current staffing levels project failure to meet periodicity of the new PM. However, funding was secured this year to begin outsourcing many PM services, making use of a pending PM IDQ contract. The key themes and programs in Norfolk's efforts listed below will be seen in many of the elements and can act synchronically for or against the manager.

Standardization

Standardization of the assets in a given asset type aided in smoothing the stock inventory process and many of the other elements as well. Using standard parts at a standardized asset does not necessarily imply that each part is from a particular manufacturer or vendor.

Norfolk has avoided a proprietary equipment scenario as much as possible by specifying control equipment, parts and pieces that are interchangeable but not manufacturer specific. Norfolk follows California Department of Transportation's specification suite for control equipment as much as possible. It arguably provides the most detailed specification set in the industry while ensuring a large pool of manufacturers and vendors because of the California's large market for equipment. Other innovations instituted in Norfolk include only maintaining a single color (black), type (LED), and two mounting types (rigid and disconnect) of signal heads in stock. To ease the labor shortage in the signal maintenance shop, specifications and orders for completely assembled traffic signal heads, control cabinets, etc., have been implemented to free time previously used by technicians in the shop and provide increased field time.

Standardization also reduces the scope of maintenance skills necessary for the maintenance group to train and maintain. Buying preassembled signal heads reduces the need to train workers to manufacture signal heads. Technicians can concentrate on replacing heads not creating them. Buying traffic control equipment with the same user interface saves the time and material necessary to train and document workers to program controllers using multiple methods. Ten years ago, it was necessary for the technician to be able to program various controllers using more than nine separate interfaces with almost as many conflict monitor interfaces. Today only two programming interfaces need be learned, soon to be reduced to one.

Standardization is a process that must be followed throughout the life cycle of the asset. It starts with the design and installation of the equipment. Maintenance must be considered as part of the design process, not only in terms of ease-of-maintenance for the asset and the reliability of the asset.

Indefinite Quantities Contract

To ensure standardization and eliminate creation of dual standards, the same specifications are used for Norfolk's signal maintenance IDQ. This important instrument provides an unlimited resource to supplement the finite in-house resource. Tasks from setting up a basic work zone through the complete construction of a signalized intersection are broken down into line item costs. Since the IDQ is awarded through a competitive bid process, it also serves as the benchmark during competitive studies for in house versus contracted costs. Norfolk has included install-only line items in this contract that allow its stock system to supply the contractor at lower cost and with tighter scrutiny of function and specification.

Price Agreements

Norfolk has also made judicious use of purchasing price agreements. For high cost, scarce or frequently used items, it makes sense to identify and advertise these items for competitive bid in purchasing price agreements. Norfolk's finance department allows traffic operations to skip normal purchasing procedures for items on a price agreement. The store keeper may order parts and material directly from the vendor. Price agreements make ordering, receiving, and testing equipment for new installations and upgrades for installation by contractors easier and more thorough as well.

LESSONS LEARNED

DOT's experience has been that changing the institutional culture is the hardest task of all. How do you move from a reactive-focused to a reliability-focused organization? To successfully transition from a traditional, repair-focused organizational culture, to a proactive, reliability-focused culture, and reap the rewards of increased performance of both equipment and people remember to follow the outline below.

Maintain a Long-Term Strategic Focus

It's easy to bend to political pressure and drop long-term plans for short-term gains. Being the voice of restraint, when a designer has council excited with expansion plans and the latest equipment can be a risky position for a maintenance manager. The maintenance manager will remember however that there is a real price to pay for expansions without a compensating increase in resources.

Aligning Reward Systems with Strategic Goals

Time should be taken to explain to technicians the reason for the switch from an "if it ain't broke don't fix it" attitude to a "fix it before it breaks" attitude. Managers and supervisors must make the rewards of preventative maintenance greater than the rewards for heroic reactive maintenance.

Strong Committed Leadership

The importance of receiving the support of management from the top down is vital. Faith and trust in the local supervisors by upper management is important to allow supervisors rather than upper managers to determine what requests can be scheduled maintenance and what requests need be reactive. Support must be given to supervisors in the difficult transition moving from reacting to planning.

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Pavement Management System
From Database to Knowledge Base

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Maryland State Highway Administration, as have many other highway agencies, built and implemented a pavement management system (PMS) for years. The utilization of the PMS has been focused on system preservation reporting and network-level rehabilitation strategy optimization. Now, an increasing number of user groups such as engineers of different interests, planners, legislatures, etc., try to use the PMS for more diversified purposes or to explore more profound knowledge. On the other hand, the PMS database is operated in a relational database management system (RDMS), which does not provide a convenient vehicle to above destinations, mainly because the RDMS emphasizes data integrity, not the knowledge embedded in the data. To safeguard the data integrity, data in a relational database generally is normalized, a process involving more tables and creating the need for more joins. As a result, many users, not armed with good knowledge of the database, find information retrieval from the PMS challenging and time consuming. This presentation outlines a strategic plan to develop a system, a knowledge base and to facilitate knowledge management of the information in the PMS. Topics cover pavement-related knowledge acquisition, representation, retrieval, and utilization.

Workforce Development

Transportation Supervisor Workforce Development for the North Carolina Department of Transportation

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The North Carolina Department of Transportation (NCDOT) recognized the need to provide a career development program for employees classified as transportation supervisors. Issues facing the transportation supervisor were the lack of managerial and technical training. The department actively took steps to address these deficiencies by developing needed training programs along with a competency-based pay program. The training programs developed include the following.

TRANSPORTATION SUPERVISORS ACADEMY

Managerial Training

Focus groups representing the four functional areas of roadway maintenance, bridge maintenance, traffic services, and roadside environmental, provided the specific details of the training needs necessary to carry out the transportation supervisor's job duties.

Training needs were identified and prioritized and the Transportation Supervisors Academy (TSA) was developed as a formalized managerial training program.

Transportation Supervisors Conferences

Technical Training

TSA began to address the managerial deficiencies of the transportation supervisor; however, there was minimal training in place to enhance technical skills for specific work functions.

In investigating technical training opportunities for transportation supervisors, it was realized that utilizing the TSA small classroom format would not provide the time frame necessary to conduct technical training. To resolve this issue, the department developed technical training modules of work functions for each functional area to be given in a conference format.

The managerial and technical training opportunities implemented have resulted in a qualified, motivated, and diverse workforce. In addition to the training, the transportation supervisors now have a career-banded competency-based pay program that enables them to earn additional income as their knowledge and skills increase as a result of their training.

Program Development

NCDOT recognized in the late 1990s the need to provide a career development program for employees classified as transportation workers and transportation supervisors. A transportation worker is the person performing maintenance activities on the more than 79,000 mi of state-maintained facilities in North Carolina. A transportation supervisor is the person directing a crew or multiple crews of transportation workers. At the time, the recruitment and retention for these positions was reaching a critical stage.

The first step taken was implementing a skill-based pay program for the transportation workers. The skill-based pay program was a career development program for the transportation worker that provides the opportunity for added compensation for each additional skill learned. Compensation is based on obtaining skill blocks related to proficient equipment operation and development of technical maintenance skills. The skill-based pay program transitioned to a competency-based pay program in which transportation workers are compensated for proficiency in specific skill sets which are directly related to the skill blocks in the original skill-based pay program. The program is divided into three levels consisting of contributing, journey, and advanced transportation workers. The program led to a highly skilled workforce that enables NCDOT to keep up with the ever-changing demands of the motoring public. Implementing the program also proved to be a morale booster for the transportation workers.

While the skill-based pay program was successful for the transportation workers, it generated problems in the transportation supervisor ranks. The additional earning opportunities the transportation workers received pushed the salary level of even the journey-level skilled workers above many of the entry-level transportation supervisors. This led to a deterioration of morale among the transportation supervisors.

The typical applicant pool for entry-level transportation supervisors is advanced-level transportation workers. In many cases the most qualified applicant refused to take the position citing minimal salary increase, no opportunity for advancement, and increased responsibility for minimal or no additional increase in salary as primary reasons. As a result of these factors, NCDOT was compelled to hire applicants with minimal managerial experience and limited technical expertise.

NCDOT actively took steps to address this deficiency by developing needed training programs and implementing a competency-based pay program for the transportation supervisors. In 2000 a statewide group representing all aspects of maintenance was convened in Raleigh. The purpose of this meeting was to review and make recommendations regarding training currently available to transportation supervisors and determine what additional developmental needs were necessary.

As a result, an advisory committee was established to pursue the development of an informal training program that would be available to all transportation supervisors. Focus groups comprised of all levels of transportation supervisors and engineers were created. These individuals provided the specific details of the training needs necessary to carry out the transportation supervisor's job duties. Those groups determined that managerial–leadership training was the most critical need followed by technical training needs.

NCDOT pursued the first critical need by developing TSA which addresses the managerial–leadership training. After successfully implementing the TSA, NCDOT organized a Transportation Supervisors Conference to address technical training. This paper includes the general purpose statement, goals, objectives and other related information regarding the TSA as well as the Transportation Supervisors Conference.

TSA PURPOSE STATEMENT

In order to meet the demands placed upon our transportation supervisors, it is imperative that we provide them with the training, awareness, and resources to carry out their job responsibilities. In doing so, it is the primary purpose of this academy to develop highly competent professional supervisors.

Academy Goal

The goal of the academy is to provide the participant with an excellent learning experience, the opportunity to share ideas and formulate different problem solving techniques, and the confidence necessary to be considered a professional supervisor thereby providing an even more professional work force to serve the citizens of North Carolina.

Academy Objectives

- Become a more effective professional transportation supervisor;
- Develop leadership skills in our transportation supervisor;
- Establish interpersonal relationships with others to accomplish tasks;
- Identify knowledge and skills needed to carry out job duties;
- Develop a working knowledge of NCDOT's structure, business practices, and mission; and
- Learn effective behavior of an individual in a supervisory role.

Once the goals, objectives, and purpose statement were in place, committees were formed to handle certain logistical concerns. These concerns consisted of, curriculum, attendance policy, academy locations, training personnel, and program oversight. The state road maintenance unit was assigned the task of selecting locations, training personnel, and development of attendance policies.

The curriculum teams agreed on a basic training philosophy where the transportation supervisors would undergo a formal training program designed specifically for them. The program draws on supervisory experience that allows them to share ideas and techniques that can be applied in varying situations that they confront daily. The participants are also challenged in developing new and innovative ways of confronting different issues. The training, highly interactive and hands-on, relies far more on group discussion, exercises, and activities rather than lectures.

The academy does not cover NCDOT policies, but emphasizes attributes of effective supervision. It is not considered corrective training, but instead is designed for those who wish to improve their supervisory performance and are willing to try innovative techniques. The participants are challenged to develop new and innovative ways of confronting different situations. The academy will make a difference in supervisors who choose to participate and apply the knowledge learned at the academy.

Curriculum

The curriculum team used the model of professional attributes in designing the academy with the projected outcome of creating professional supervisors. Those attributes are defined below.

Leadership

Leadership consists of using appropriate supervisory styles and methods to guide individuals or groups to accomplish a task.

1. Plan: develop a course of action for self or others to accomplish specific tasks.
2. Organize: arrange and group tasks, allocate resources, and set schedules so that activities can be accomplished as planned.
3. Task assignment: designate roles in accomplishing the planned work schedule.
4. Monitor results and follow up: measure actual performance, compare results with work standards, and give appropriate feedback.
5. Resource management: plans for allocation of personnel, time, budget, material, and equipment.
6. Leadership styles: the exercise of supervisory power through various techniques to motivate and guide employees in accomplishing work tasks.

People Skills

People skills require the ability to establish interpersonal relationships with others to accomplish work tasks.

1. Understand others: Use perception and analysis to draw conclusions or make judgments as to the message or intent of others' behavior.
2. Communications: send and receive information through verbal, written, nonverbal, electronic messaging, and public speaking.
3. Meeting skills: conduct meetings to accomplish the agenda.
4. Persuasion: influence the actions and thinking of others through the use of appropriate techniques.

Job Competency

Job competency is the ability to do one's own job.

1. Knowledge: abilities developed from training or education.
2. Experience: abilities gained from the performance of the job.
3. Work standard assessment: continuous evaluation of work processes and results.

Organizational Knowledge

Organizational knowledge consists of a basic understanding of the organization's structure, business practices, and mission.

1. Right of way to right of way vision: integration of all activities performed within defined area of responsibility.
2. System input: willingness to contribute and receive information, facts, or data to improve the system's effectiveness.
3. Structural awareness: understand and follow the chain of command.
4. Compliance with business practices: follow accepted guidelines, procedures, and standards.

Personal

Personal is the development of effective behaviors of an individual in a supervisory role.

1. Ethics and pride: set and reach high goals and standards of personal behavior.
2. Credibility: establish a reputation for being honest and trustworthy.
3. Role model: lead by example.
4. Tolerance for stress: work well under pressure.
5. Initiative: take action beyond what is required to achieve work goals.
6. Adaptability: ability to deal with different types of people and situations while remaining effective.
7. Judgment: use experience and knowledge to determine the proper course of action.
8. Problem solving–decision making: ability to analyze issues or situations and reach a conclusion or take appropriate action.

Group Dynamics

Group dynamics consists of developing the ability to form relationships, work with others and get others to work efficiently (Figure 1).

FIGURE 1 Group dynamics consists of developing the ability to form relationships, work with others, and get others to work efficiently.

1. Develop employees: provide opportunity for employee personal and professional growth.
1. Manage conflict: bring resolution to disagreement and disputes in a work environment.
2. Collaboration: work effectively with others outside the line of formal authority.
3. Team building: the ability to guide the process in which individual employees work collectively toward a common goal.

Training

The team decided upon two separate levels of training with each level targeted at different audiences. The first level, Fundamentals of Supervision, consists of two 3-day sessions and addresses the development of interpersonal attributes. This class is available to all supervisors and is a prerequisite to the second level.

Sessions in this level include extensive group activities (Figure 2) with modules that examine topics such as the following:

- Delivering services to the public. Emphasis is placed on understanding others, communications, compliance with business practices, tolerance for stress, and problem solving–decision making.
- The merits of good leadership: the attendees are asked to prepare list of those attributes that exemplify good leaders. Discussions of how the effects of poor leadership impact the department, the employees, and the citizens of our state.
- Manage diversity. Attendees are exposed to the different areas of diversity faced within the work environment and are given scenarios in which they evaluate and development appropriate management skills.
- Basic management skills consist of dealing with planning and organizing work, task assignment, resource management, right-of-way to right-of-way vision, collaboration, and team building.
- Communication techniques focus on skills such as persuasion, meeting skills, public presentations, and communicating while under stress.
- Organizational skills include resource management, job knowledge, job experience, structural awareness, role model, judgment, and developing employees.
- Manage conflict. Techniques discussed are monitoring performance, establishing measurements, evaluating results and follow-up. Other techniques include understanding others, persuasion, work standards assessment, tolerance for stress, and employee development.

The second level of the academy shifts to understanding role differences as the supervisor’s career and responsibility advances. The advanced supervisory techniques consist of two 3-day sessions. This level is designed more toward the supervisor whose responsibilities encompass multiple crews or projects. Sessions in this level include extensive group activities with modules that examine topics such as the following:

FIGURE 2 Sessions in Fundamentals of Supervision (above) include extensive group activities.

- The changing roles of the supervisor discussed what a supervisor's roles and responsibilities' are today versus just 5 years ago and what will they be 5 years from now.
- Personnel action techniques are developed in such areas as understand the hiring process, the interviewing process including the interview itself and preparing the interview record, understanding the importance and issues of orientation and socialization of new employees, the concepts and processes of disciplinary action including documentation, counseling, consultation with immediate supervisor, and conducting follow up
- Stress management identifies the signs of stress and its impact on themselves, their employees, NCDOT, and its customers, discusses the ability to recognize the sources of stress, how to cope with stress, and how to practice stress management
- Contract supervision: attendees review the general types of NCDOT maintenance contracts, discuss the different roles of transportation supervisors in contract supervision, identify the pros and cons of contracting tasks for NCDOT, transportation supervisors, and transportation workers, explore issues with contract supervision and practice skills for dealing effectively with those issues.
- Dealing with on-the-job emergencies. Attendees review the types and scope of emergencies in NCDOT, define the roles of the supervisors at each level during and after the emergency, discuss the elements involved in planning for emergencies and practice the needed skills. Identify problems that can occur in responding to emergencies and identify strategies for dealing with the problems managerial aspects.

TRANSPORTATION SUPERVISORS ACADEMY SUMMARY

Academy Overview

NCDOT is committed to the career development of its supervisors. The managerial and technical training opportunities implemented have resulted in a qualified, motivated, and diverse workforce. NCDOT's supervisors now have a career-banded competency-based pay program that enables them to earn additional income as their knowledge and skills increase as a result of their training (Figure 3).

TSA enables supervisors to receive formal management training. The academy focuses on the supervisor discovering better ways of planning, organizing, implementing, and evaluating the duties associated with their job.

The goal of the academy is to provide an even more professional work force to serve the citizens of North Carolina. In doing so, we will also serve ourselves.

Upon completion of the academy, the participants take the attributes and techniques developed during the training back to their respective units and apply them.

Feedback from the attendees has been very positive and those attending have whole heartily promoted the academy to their peers (Figure 4). Some typical comments are "This is the best training I have ever received," "My boss needs to be here," and "The opportunity to network with other supervisors is as good as the training."

FIGURE 3 The managerial and technical training opportunities implemented have resulted in a qualified, motivated, and diverse workforce.

FIGURE 4 Feedback from the attendees has been positive and those attending have wholeheartedly promoted the academy to their peers.

Evaluation

Evaluating the impact of the academy is accomplished by pre-academy and post-academy assessments completed by the attendee and the attendee's immediate supervisor (Figure 5). Personal interviews are also conducted with both the attendee and the immediate supervisor to determine if skills learned at the academy have been utilized since completion (Figure 6).

The post-academy interviews are very positive from the attendees and their immediate supervisors. The most repeated comment from the attendees was "my boss needs this training." The most prevalent comment from the immediate supervisors was "when can I send the rest of my supervisors?"

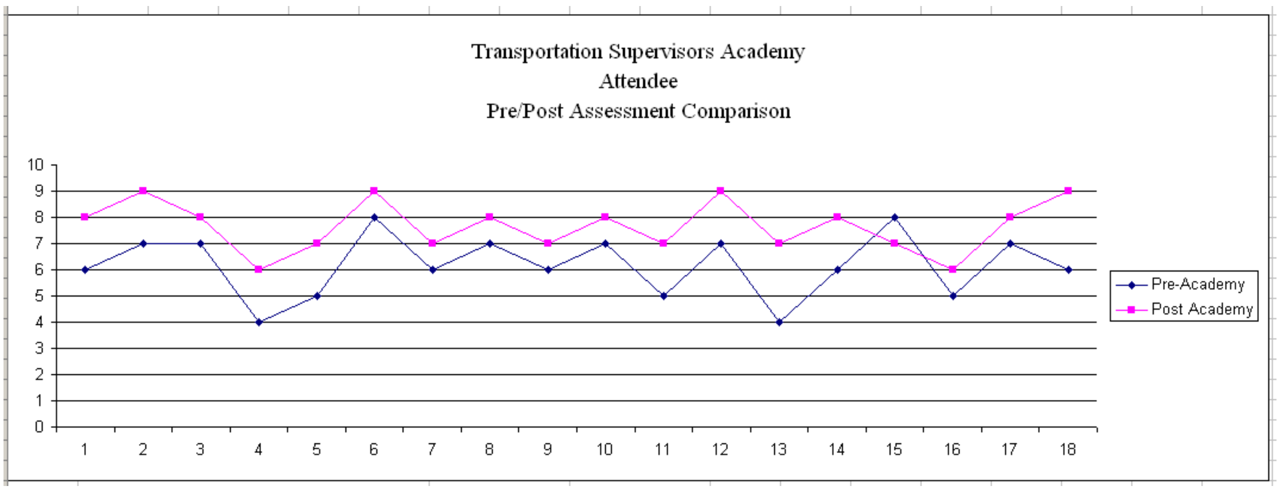

FIGURE 5 Pre- and post-assessment comparison.

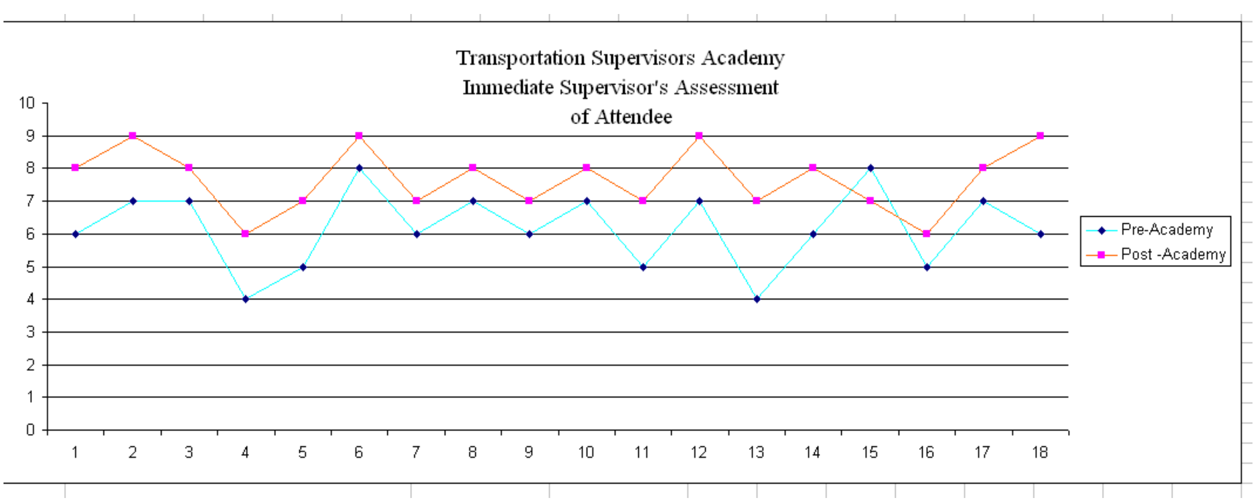

FIGURE 6 Supervisor's assessment of attendee.

TRANSPORTATION SUPERVISORS CONFERENCE

While the academy focuses heavily on the human recourses and personnel the need for technical training still existed. The state road maintenance unit began investigating technical training opportunities for the transportation supervisors in May 2006. The idea was to examine the possibility of adding a series of technical training classes to enhance the academy.

One of the obstacles with adding technical training to the academy was delivery time. It would take years to reach all the supervisors with the training format of the academy. In the process of preparing and evaluating the technical training plan, a better alternative presented itself. It was during this development process that the idea of a training conference was discussed and proposed.

Situation Analysis

It is generally accepted that statewide, there are varying methods of even the most basic operations. The differences vary from division to division, county to county, and even down to crew versus crew. While some of these variances are necessary due to climate, terrain, and equipment, some are simply due to lack of understanding of policies and procedures. Among the transportation supervisors there is also a strong desire to understand the reasons why we operate the way we do.

Currently almost 1,000 transportation supervisors work for NCDOT. To implement a technical training plan that would be conducted in a class size of 24 participants at a time was not reasonable therefore a conference setting was chosen.

Conference Development Plan

A conference committee was organized and was charged with a number of tasks. This included

- Determine a host facility or facilities that could accommodate the conference;
- Develop an agenda for the conference that will encompass all training objectives;
- Work with senior management, to develop a curriculum that will prioritize needed training modules;
- Identify and overcome logistical obstacles that would interfere with the facilitation of completing six conferences over 8 weeks to be held at three locations and serving 1,000 participants; and
- Develop roles for the specific groups and identify expectations of the groups.

JUSTIFICATION OF TRAINING

In many cases, proper training makes the difference in meeting or exceeding budget expectations, and in the case of safety training it could mean the difference between life and death. This training should result in the faster completion of assigned tasks, fewer errors, and a general reduction in operational cost. In addition technical training will:

- Improve consistency of technical operations in field;

- Create a venue for new ideas by encouraging participant's input during group discussion;
- Identify improved methods of operation by analyzing feedback from participants;
- Identify operational problems and provide opportunities to discuss solutions; and
- Further the overall goal of the academy by continuing to encourage the transportation supervisor to accept management responsibility.

Training Plan

Training plan design allows for general sessions, functional group specific breakout sessions, and core breakout sessions for all attendees (Figure 7). The conference was designed as a 3-day event with the general session on the opening day augmented by one group of the universal or core training. The second day was reserved entirely for functional group specific modules. The final day was for the remaining universal or core sessions.

- General session training consisted of presentations by the senior management team with a group question and answer session as well as a presentation from the departments safety and loss section.
- Universal (core) training included modules of incident response, disaster recovery, maintenance management systems–work functions, and an environmental workshop.
- Functional group specific training was designed by each functional group: bridge maintenance, road maintenance, roadside environmental, and traffic services.

In order to provide consistency a unilateral approach to all the technical topics was taken by reviewing the maintenance operations manuals related to subject matter along with describing the information as the recommended Generally Accepted Best Methods. At the end of this review the facilitators prompt discussion as to what is working best in the different locations. This training method proved to be successful the discussions were recognized by the attendees' evaluations as some of the most beneficial aspects of the conference.

FIGURE 7 The technical topics specific to functional groups presented a problem almost at the outset of planning. There are 14 divisions in the department and they are subdivided into 40 districts, each believing its own work pattern is the ideal.

The trainer–facilitator then shifts focus toward managerial theory, why, and how to supervise this activity. This shift is important because the goal of this training is to improve managerial practices before, during, and after operations. The trainer–facilitator prompts discussions on four supervisory competencies; these are deemed the essential competencies needed to manage operations efficiently and are the measurements for the transportation supervisors competency-based pay program.

Leadership Modules

While each functional group designed its own presentation, they were asked to incorporate into their presentations attributes that parallel the competency-based pay program of supervisors.

PLANNING AND ORGANIZING

Why Is Planning Important?

Daily operations for the transportation supervisor are difficult even on the best days. Lack of planning leads to indecisiveness. Starting the day with a variety of personnel issues accompanied by indecision will overwhelm the lesser-experienced supervisor and potentially even an experienced one. Proper planning will provide the supervisor with a level of comfort enabling the supervisor to better adjust to any changes.

What Should You Consider When You Plan?

- Define your unit's objectives and goals.
- Prioritize tasks.
- Determine work to be accomplished.
- Determine manpower needs.
- Determine equipment requirements.
- Determine materials needs.
- Allocate funds.
- Plan alternatives for the unexpected surprises.
- Know current inventories of available assets such as materials, equipment, and manpower.
- Position unit to adapt to changing priorities such as inclement weather, accidents, funding shortages, etc.

OPERATIONS

Pre-Operations

- Check inventory to assure necessary materials are available.
- Check tools (chainsaws, augers, etc.) to assure they are available and in good working condition.

- Check equipment availability and working condition.
- Review manpower needs to assure best utilization of man hours.
- Determine work zones are set up properly and all other traffic control measures are taken.
- Coordinate with other DOT personnel, governmental agencies, private entities, and general public.
- Secure all necessary permits–authorizations.

Field Operations

- Ensure work zones are set up according to all traffic control manuals and guidelines.
- Direct work activities to assure they are performed in accordance with applicable policies and procedures.
- Make any adjustments necessary to work assignments, work schedules, and work flow to accommodate changing operational needs (balance daily work flow, project changes, training needs).
- Interact with DOT personnel, other governmental agencies, private entities, and the general public in a timely and professional manner.

Post-Operations

- Ensure employees are aware of proper disposal procedures and proper disposal locations.
- Ensure employees properly clean and store equipment and tools.
- Ensures employees determine and communicate to management any needed repair of equipment or tools.
- Records daily work activities properly utilizing Fr1101s, SAP, and maintenance management system (MMS).
- Keep immediate supervisor apprised of status of operations.

Performance Evaluating–Measurement

- Ensure quality of work is performed in accordance with applicable policies and procedures.
- Ensure quantity of work performed is in a timely and efficient manner. Work quantity should be checked by comparing manpower, work site locations, equipment, material availability, and work accomplished against past performances.
- Follow established DOT safety policies and procedures relative to maintaining a safe work environment.
- Operate within an established unit cost for assigned tasks and be able to determine cost over runs–under runs.
- Utilize data from MMS to track work accomplished, tasks, and budget.

HUMAN RESOURCE MANAGEMENT

- Resolve informal complaints before, during, or after operation
- Use formal disciplinary actions if necessary.

FISCAL

- Review fiscal records for accuracy (Fr1101s).
- Ensure operational costs are consistent.
- Record data in MMS.

TECHNICAL MODULES

The scope of work for the focus group was to perform a needs assessment of the training requirements for their respective supervisors and development of presentations. Each group was given the time frame of each module and told to adjust their presentations to fit. The groups presented the following topics:

Functional Group: Maintenance

- Pavement preservation;
- Pavement maintenance;
- Shoulder and ditch maintenance; and
- Force account construction.

Functional Group: Traffic

- Pavement markings: leftovers, new left-turn layout, roundabouts layout, special markings (railroad, schools), sight distance layout;
- Pavement markings incentive program;
- Signing: sheeting, nighttime review, proper installation;
- Temporary traffic control: detour routes, incident traffic control, slow-moving operations; and
- Reference materials, how and when to use them: *Manual of Uniform Traffic Control Devices*, TEPL, Standard Specifications.

Functional Group: Bridge

- Large pipe installation and maintenance;
- NCDOT inspections;
- Life cycles of bridges; and
- Safety in bridge maintenance.

Functional Group: Roadside Environmental

- Pesticide management;
- Nutrient management;
- Plant bed maintenance;
- Roadside performance measures;
- Roadside asset inventory;
- Preventing storm water pollution; and
- Seeding, mulching, and matting.

TRANSPORTATION SUPERVISORS CONFERENCE SUMMARY

In the early spring of 2008 1,000 transportation supervisors from North Carolina's 14 highway divisions assembled in three locations over an 8-week period to participate in technical training designed exclusively for their position (Figure 8). The conferences were held in centralized locations to help defray travel cost. All participants were urged to utilize the overnight accommodations in hopes of them taking advantage of the networking opportunities.

The technical training topics for each functional group were relevant to their daily work activities and instrumental in providing the knowledge, skills, and techniques to performing these activities correctly and efficiently. The transportation supervisors enjoyed the opportunity for formal and informal discussions both of which enhanced their technical supervisory skills.

There was also instrumental support from NCDOT management in conducting the supervisor conferences (Figure 9). The division engineers for all 14 divisions were very supportive of the training effort and realize the benefit this training has in the proficiency of their

FIGURE 8 In 2008 1,000 transportation supervisors from 14 highway divisions assembled in three locations over an 8-week period to participate in technical training.

FIGURE 9 NCDOT management was instrumental in conducting the supervisors conferences.

supervisors. Representatives from the chief engineer of operations office attended each training session and facilitated a question-and-answer session and met personally with the supervisors. This effort was noticed by the attendees, as it was repeatedly emphasized that they were the backbone of this organization.

CONCLUSIONS

In summary, NCDOT has realized the importance of developing transportation supervisors with the managerial and technical skills required to lead this organization.

By implementing the TSA and the transportation supervisor conferences, NCDOT is successfully developing professional transportation supervisors. With dedicated funds, training, and upper management support, the transportation supervisors are prepared to be on the front lines in providing good transportation services to the traveling public in North Carolina.

Management Aspects
of Winter Services

Cost–Benefit Analysis of the Pooled-Fund Maintenance Decision Support System
Case Studies

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FHWA funded and marshaled collaboration among six national research centers and a pool of maintenance practitioners from several state departments of transportation (DOTs) to develop a functional prototype maintenance decision support system (MDSS). In an effort to practically apply the MDSS concept, a pooled-fund study (PFS), led by the South Dakota DOT and including eight other states along with Meridian Environmental Technology, has built on this effort by developing an operational MDSS that satisfies the needs for these states. Based on the PFS led by South Dakota DOT, this paper presents the analysis results of MDSS benefits and costs. The study first identifies the tangible and intangible benefits and costs associated with MDSS implementation. A simulation methodology is then developed in this study to quantify the benefits including resource savings, safety savings, and delay savings. Different simulation scenarios are proposed for the benefit–cost analysis, by using different levels of service and resource usages. Finally, the methodology is applied to multiple case study states, which represent different climates.

Significant weather-related costs are incurred by maintaining highways in the United States. State and local agencies spend more than $2 billion annually on snow- and ice-control operations (*1*). The enormous amount of resources spent on winter maintenance, along with concerns over traffic safety, mobility, and corrosion and environmental impacts, have stimulated transportation agencies to explore and adapt more efficient strategies (e.g., anti-icing) for snow- and ice-control.

The effective use of winter maintenance strategies requires advanced technological support from road weather information, vehicle-based sensor technologies, materials, decision support systems, and other sources. With such support, it is generally expected that an agency can reduce the materials, equipment, and labor resources it expends on winter maintenance, while simultaneously returning the road to normal driving conditions more quickly. Nevertheless, the integration of information and technology is a challenge to transportation agencies. One of the initiatives that respond to this challenge is the use of a maintenance decision support system (MDSS).

MDSS is an integrated software application that provides users with real-time road treatment guidance for each maintenance route, addressing the fundamental questions of what, how much, and when according to the forecast road weather conditions, the resources available, and local rules of practice (the methods that a transportation agency uses in treating its roadways). In addition, MDSS can be used as a training tool as it features a what-if scenario treatment selector that can be used to examine how the road condition might change over a 48-h period with the user-defined treatment times, chemical types, or application rates.

In 2002, a pooled-fund study (PFS), led by South Dakota Department of Transportation (DOT) and now including 13 state DOTs, formed to establish an operational MDSS that meets or exceeds the federal vision of a MDSS (*2*). To date, the PFS MDSS has been demonstrated in pooled-fund states. While generally perceived to be beneficial, it is important to more formally determine the benefits and costs that are associated with the implementation of MDSS, and determine whether MDSS is a good investment.

The objective of this study is to develop a methodology for benefit–cost analysis (BCA) of the pooled-fund MDSS. The paper first describes background information about MDSS. A methodology is then proposed for analyzing tangible benefits and costs associated with the deployment of the pooled-fund MDSS. The methodology is applied to a case study for BCA. Finally, discussion and findings of this study are presented.

BACKGROUND

The fundamental principle behind the development of the MDSS is the truism that better information leads to better decisions. MDSS applies this truism specifically to weather information, pavement surface condition, and winter road maintenance decisions. MDSS aims to provide weather and road condition forecasts and real-time treatment recommendations (e.g., treatment locations, types, times, and rates) for specific road segments, tailored for winter road maintenance decision makers. With the right information, winter maintenance managers can respond proactively by managing the infrastructure and deploying resources in real time.

There are two development tracks associated with MDSS that are important to consider when defining MDSS. The first development track has been led by FHWA. In 2000, FHWA conducted a user needs assessment for surface transportation weather information. As a result, FHWA engaged a pool of maintenance practitioners from several state DOTs and researchers from several national laboratories with expertise in weather forecasting and winter road maintenance to develop a prototype winter MDSS. A prototype was developed that was designed to address the end user needs and to facilitate the rapid implementation by the private sector and transportation agencies. FHWA's functional prototype MDSS capitalized on existing road and weather data sources and the state-of-the-art weather forecasting models and data fusion techniques.

A second development track emerged early on when several states realized that the prototype MDSS was not going to meet their operational needs. This track was supported by FHWA, which intended for states to work with the private sector in developing customized applications to meet state DOTs' needs. Examples of these applications are the pooled-fund MDSS and the Maine DOT MDSS. The development of these MDSS is different from the FHWA prototype MDSS in that it focused on operations and tactics while the FHWA one focused on strategies.

The Maine DOT MDSS was developed by DTN/Meteorlogix based on the federal prototype MDSS, and include capabilities to meet DOT's needs. Cluett and Jenq (*3*) assessed the benefits and lessons learned associated with the use of the Maine DOT MDSS. A 12-mi Interstate highway segment was used for this study during the winter of 2006–2007. The study indicated that Maine DOT personnel benefited from this season with the deployment of MDSS. This study, however, did not provide quantitative assessment of cost savings from using the MDSS, due to the lack of baseline data in a before–after system design (MDSS deployment prior to the initiation of evaluation).

The MDSS PFS, led by South Dakota DOT and including 13 state DOTs, was formed to develop an enhanced version based on the federal MDSS prototype. The PFS contracted with Meridian Environmental Technology to develop the operational prototype, which can be programmed to give guidance according to an agency's rules of practice, or be used to prescribe a scientifically optimal treatment based on the resources that the agency has at its disposal.

METHODOLOGY

The objective of this study is to assess the benefits and costs associated with the pooled-fund MDSS. While both quantitative and qualitative assessments are conducted, this paper focuses on quantitative evaluation of the pooled fund MDSS benefits and costs. The methodology followed mainly includes three steps: the identification of winter maintenance benefits and costs, definition of base case and alternatives, and development of the benefit–cost model.

Identification of Benefits and Costs

To identify the benefits and costs associated with the use of MDSS, extensive interviews with pooled-fund stakeholders were conducted. Through the interviews, the study sought to understand the objectives of agencies' snow- and ice-control operations, potential benefits and costs associated with MDSS implementation, and the availability of data to support quantitative analysis. The surveys showed that mobility and safety were primary objectives of winter maintenance operations. While other objectives such as environmental stewardship and cost effectiveness were mentioned, mobility and safety were paramount.

It is important to recognize that winter maintenance operations technically do not directly affect either mobility or safety. Winter maintenance operations focus on improving pavement conditions during and after winter weather events. Many studies have documented that crash rates increase significantly during winter weather conditions, and that vehicle speeds drop during those conditions as well (*4*–*9*).

BCA traditionally considers three groups when quantifying benefits and costs: agencies, users, and society. Winter maintenance activities clearly have benefit and cost impacts on all three of these groups. The social benefits and costs related to winter maintenance activities, including effects on water quality, wildlife habitat, air quality, pavement integrity, and infrastructure corrosion are meaningful but extremely complex to evaluate and generalize. Therefore, this analysis focuses on agency and user benefits and costs. To avoid confusion between the users of MDSS and the users of the treated roadway system, this analysis distinguishes between agency benefits and costs, and motorist benefits and costs. Since motorists have no direct cost in the usage of MDSS, there are three components included in this evaluation methodology: agency benefits, motorist benefits, and agency costs. Taxonomy of these benefits and costs are provided in Table 1. For consistency, reductions in agency costs are treated as

TABLE 1 Taxonomy of MDSS Benefits and Costs

	Agency	User	Society
Benefit	**Reduced materials costs** Reduced labor costs Reduced equipment costs Reduced fleet replacement costs Reduced infrastructure damage due to road salts	**Reduced motorist delay [through improved level of service (LOS)]** **Improved safety (through improved LOS)** Reduced response time Reduced clearance time Reduced vehicular corrosion due to road salts	Reduced environmental degradation
Cost	**Software and operations costs** **In-vehicle computer hardware investment** **Training** **Communications costs** **Weather forecast provider costs** **Administrative costs**		

Note: Bold indicates included in methodology.

agency benefits (e.g., resource savings). The bold items (tangible benefits and costs) in this table will be included in the analysis. The tangible benefits for user include reduced delay and improved safety.

Definition of Base Case and Alternatives

BCA typically relies on a clearly defined base case. However, in the case of pooled-fund states, there is no clear consensus of base cases across the states. Different states employ a variety of information and treatment tools, and also have different accounting management structures.

In addition to the base case, BCA uses a set of well-defined alternatives for comparison. In this case, the MDSS implementation alternatives are not obvious. There are a variety of ways in which a transportation agency may choose to implement the pooled-fund MDSS. First, the MDSS currently uses weather forecasts created by Meridian, the contractor responsible for system development and support; however, the software has been designed to accept forecast input from other sources. Second, the ability of MDSS to accurately forecast future pavement conditions depends on an accurate understanding of maintenance actions and weather conditions in the past and present. Thus, a feedback mechanism is required so that the MDSS can know what treatment options have been executed on routes. The pooled-fund MDSS provides two general options for this: manual reporting and mobile data collection (MDC). Third, pooled-fund states have different approaches for making treatment decisions. In some cases, decisions are made at a supervisor level and are exactly executed by vehicle operators. In other cases, vehicle operators have significant leeway and discretion in making decisions. In the latter case, some states may use MDC or in-vehicle graphical user interface that provides information on the current treatment recommendations. Currently, there are two levels of MDSS usage: using it mostly as a source of integrated road weather information, or using it also for the specific road treatment recommendations during operations and personnel training.

As mentioned earlier, the objective of winter maintenance operations is to restore the pavement to normal operations more quickly. Thus, the definition of the base case and alternatives are based on the operational philosophy that the LOS, here defined as a quasi-quantitative measure of pavement conditions during winter storm events, improves only with an increase in resources (e.g., personnel, materials).

The relationship between LOS and winter maintenance costs is illustrated in Figure 1. An agency operating under a baseline condition following its standard rules of practice, might operate at point 1. Additional or fewer resources would move the agency along the curve labeled baseline. If an agency implements MDSS, it is anticipated that this would move the agency to a curve labeled MDSS, on which it is assumed that the same level of resource investment would yield a better LOS. It is not clear where on curve the agency might fall. Based on the illustrated relationship, this study defines three different scenarios for BCA.

- Scenario 1 (base case): under a baseline condition by following rules of practice (without the use of MDSS); this is referred to as control scenario.
- Scenario 2 (alternative): keep the winter maintenance costs constant but with the option of following MDSS treatment recommendations; this is referred to as same resources scenario.

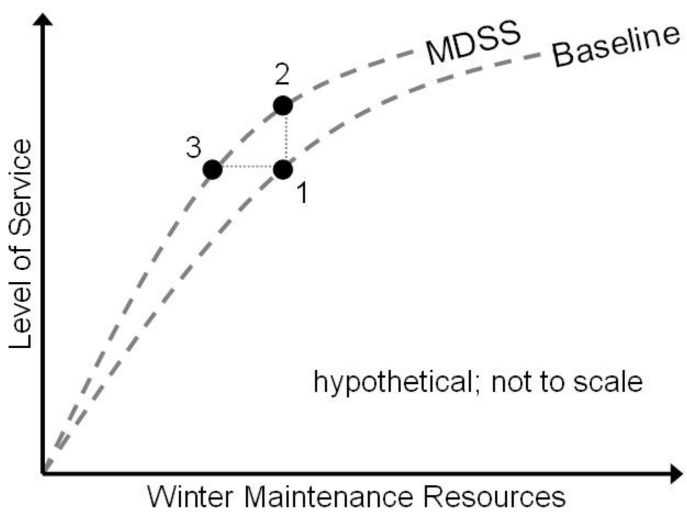

FIGURE 1 Relationship between LOS and costs.

- Scenario 3 (alternative): keep LOS constant but with the option of following MDSS treatment recommendations; this is referred to as same condition scenario.

Development of Benefit–Cost Model

As illustrated in Figure 1, the use of MDSS may affect both winter maintenance costs and the LOS achieved. Conceptually, the benefits of MDSS can be measured by comparing the two curves in the figure. This is complicated by several issues, primarily transportation agencies' general lack of actual LOS measurements that could be used to derive the baseline curve. Even if the baseline curve were known, one would need to know where on the MDSS curve between the same resources and same condition scenarios the agency chose to balance the tradeoff between costs and LOS.

In the absence of actual LOS data, we propose that MDSS itself be used as a tool to simulate the LOS that will result from various maintenance actions. Controlled scenarios can be established to compare the results of applying MDSS recommendations (i.e., MDSS curve) with those achieved through following the rules of practice (i.e., baseline curve). It is then possible to run MDSS to achieve Point 2 (same resources) and estimate LOS benefits, or to achieve Point 3 (same condition) and estimate winter maintenance resource usage benefits.

Figures 2 and 3 show how MDSS was used as a simulation tool to support the BCA. The methodology consists of two modules: the baseline data module and the simulation module. In the process of benefit analysis, these two modules progress in a parallel sequence instead of a serial sequence. In the baseline data module, various data, including highway route information (step 1), winter maintenance resource usage data (step 2), traffic volume (step 3), crash data (step 4), and weather information (step 5), are incorporated to establish detailed baseline information for each route segment. In step 3, truck and nontruck data are tracked separately because trucks have a higher value of travel time. In the simulation module, steps 6 to 8 are used to generate simulation output from MDSS for the each of the three scenarios, based on the inputs of selected route segments for simulation, weather data, daily resource usage data, and rules of practice. The process of simulation includes model establishment for a route segment, calibration, and validation. Output from simulation mainly includes pavement conditions (LOS information) and maintenance information by hour. The process of simulation takes considerable effort even for a route segment. Thus, for a given state, it is recommended that only a few representative sites are used for simulation instead of several hundred highway segments. The representative sites must have good records regarding historical maintenance activities, documented rules of practice, and a nearby weather station. The simulation output from selected route segments are then extrapolated to other route segments within the state.

The classification of storm events in steps 5 and 9 connects the baseline data module with the simulation module. In step 5, weather data are obtained from weather stations that have sufficient historic data. Winter storm events (that have at least 1 h of moisture, either as precipitation or condensation, on the roadway) are identified according to a series of weather parameters. As shown in Table 2, the parameters include air temperature, storm duration, precipitation accumulation, precipitation rate, average wind speed in storm, average wind speed after storm, and condensation. Each parameter includes a range of values, and each storm event consists of eight values with each representing a value of the associated parameter. Obviously, there are a large number of potential events with different parameter values under this concept.

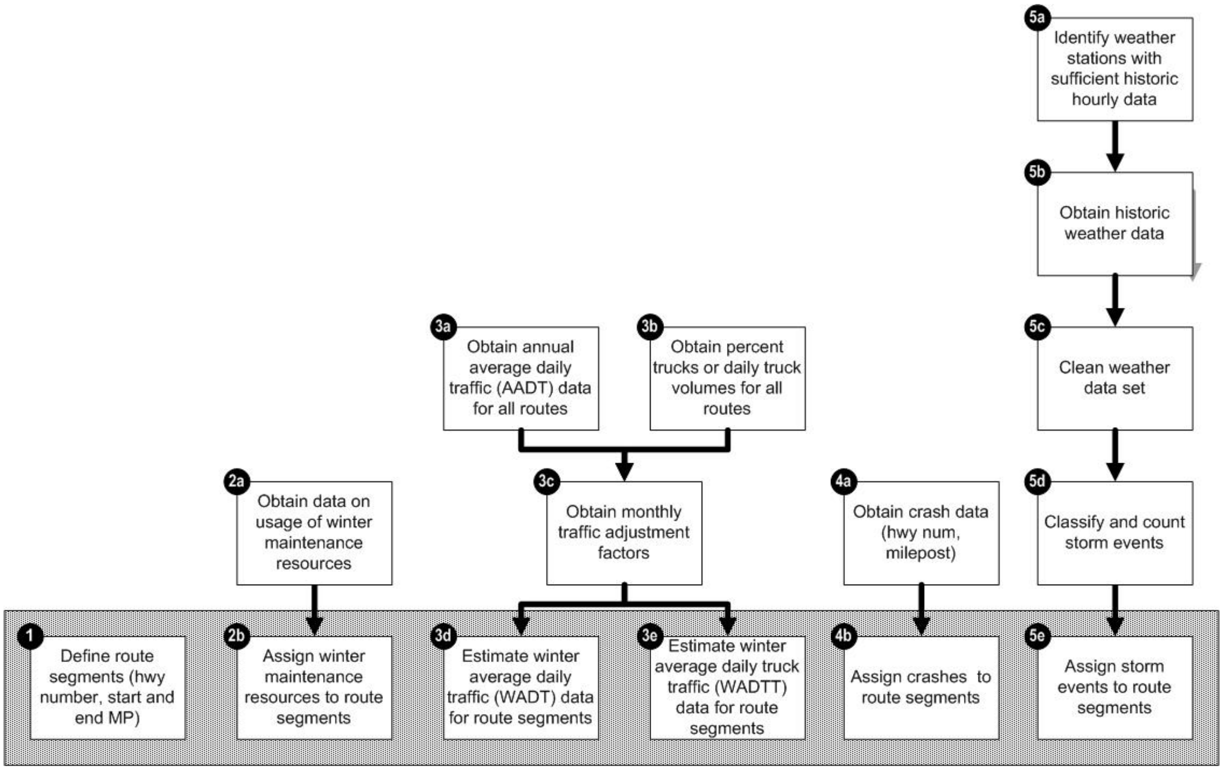

FIGURE 2 Baseline data module.

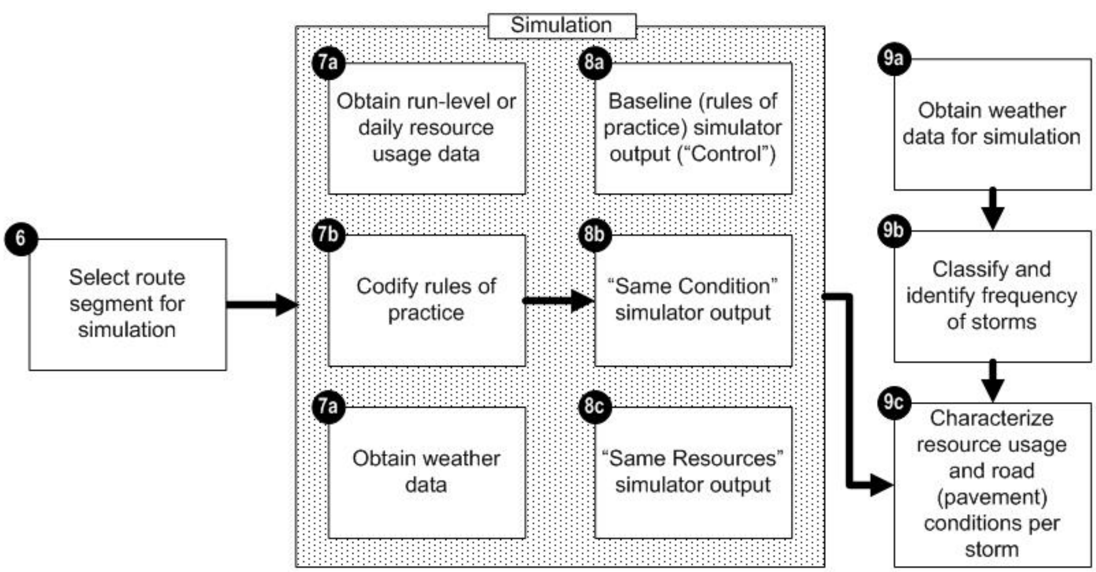

FIGURE 3 Simulation module.

TABLE 2 Weather Parameter Values for Classifying Storms

Parameter	How Collected	Range	Value
Air temperature range (T_{range})	This is based on the average of air temperature observations collected during the storm.	Warm: 32°F < temperature range	$T_{range} = 4$
		Mid range: 25°F < temperature range ≤32°F	$T_{range} = 3$
		Cool: 15°F < temperature range ≤25°F	$T_{range} = 2$
		Cold: temperature range ≤15°F	$T_{range} = 1$
Pavement temperature trend (T_{trend})	This is based on the difference between the temperature at the beginning and end of the storm events.	Warming: (end temp.) – (beginning temp.) > 2°F	$T_{trend} = 3$
		Steady: 2°F ≥ (end temp.) – (beginning temp.) >= –2°F	$T_{trend} = 2$
		Cooling: (end temp.) – (beginning temp.) < –2°F	$T_{trend} = 1$
Duration (D)	This is the number of hours included in the storm event.	1–2 h	$D = 1$
		3–4 h	$D = 2$
		5–8 h	$D = 3$
		9–12 h	$D = 4$
		13–24 h	$D = 5$
		Over 24 h	$D = 6$
Precipitation accumulation (P_{acc})	This is the sum of water equivalent precipitation encountered during the storm.	No accumulation	$P_{acc} = 0$
		0 < accumulation < 0.1 in.	$P_{acc} = 1$
		0.1 ≤ accumulation < 0.25 in.	$P_{acc} = 2$
		0.25 ≤ accumulation < 0.50 in.	$P_{acc} = 3$
		0> 0.50 in.	$P_{acc} = 4$
Precipitation rate (P_{rate})	This is the quotient of P_{acc} over D.	No precipitation rate	$P_{rate} = 0$
		0 < rate < 0.05 in./h	$P_{rate} = 1$
		0.05 in./h ≤ rate ≤ 0.10 in./h	$P_{rate} = 2$
		0.10 in./h < rate	$P_{rate} = 3$
Average wind speed in storm (W_{storm})	This is the average wind speed observation during the storm.	Wind speed < 2 mph	$W_{storm} = 0$
		2 mph ≤ wind speed ≤ 10 mph	$W_{storm} = 1$
		Over 10 mph	$W_{storm} = 2$
Average wind speed after storm (W_{post})	This is the average wind speed observation during the 4 h after the storm.	Wind speed ≤ 10 mph	$W_{post} = 1$
		Wind speed > 10 mph	$W_{post} = 2$
Condensation (C)	This refers to whether the ambient temperature is equal to the dewpoint.	(Air temperature) – (Dewpoint/frostpoint) > 2°F	$C = 0$
		(Air temperature) – (Dewpoint/frostpoint) ≤ 2°F	$C = 1$

Thus, storms events need to be further classified into a certain number of groups. Cluster analysis method was used for this purpose. While there are many existing techniques for cluster analysis, the k-means method (*10*) is used in this study as it is more suitable for cluster analysis when the sample size is large (e.g., >200).

K-means is a simple procedure to classify a given dataset through a certain number of clusters (assume *k* clusters). The algorithm of *k*-means aims at minimizing an objective function. The objective function is

$$J = \sum_{j=1}^{k} \sum_{i=1}^{n} \left\| x_i^j - c_j \right\|^2 \tag{1}$$

where $\left\| x_i^j - c_j \right\|^2$ is a distance measure between a data point x_i^j and the cluster center c_j, and J is an indicator of the distance (squared Euclidean distance) of the n data points from their respective cluster centers.

Once the storm events are clustered, the number of storm events per winter season for each cluster (storm type) can be calculated for each route segment, and step 5 is finished.

In step 9 of the simulation module, the storm events are also identified according to weather parameter values in Table 2, based on the weather data collected for simulation. Each storm event is then matched to one of the *k* clusters determined in step 5. The minimum squared Euclidean distance in Equation 1 is used for matching storm events to clusters. The matching means that the baseline data module and the simulation module are connected and the simulation results can be applied to the baseline data module. In step 9c, resource usage and road conditions are characterized for each storm type. With this, the average resource usage (e.g., amount of material used per storm type per lane mile) and the average duration under various road conditions (e.g., number of hours under slushy pavement condition per storm type) can be calculated for each storm type, and for each scenario. The average values are further applied to the baseline data module for benefit analysis. An assumption of the application is that storms of the same type will require a similar winter maintenance response (e.g., resource usage).

The benefit analysis of resource usage is relatively simple. The resources used for each scenario can be easily obtained, given the number of events per storm type per season (derived from step 5e) and the values of resource usage (derived from step 9c). The benefit analysis for resource can then be conducted through comparing the total resources used in different scenarios. Delay and safety benefit analysis of MDSS is more difficult than that of resource usage. As discussed earlier, the improvement of safety and reduction of delay can be realized through improving LOS, which is characterized by road (pavement surface) conditions. Thus, safety and delay benefits can be analyzed through relating road conditions to safety and delay. In light of this, it is important to identify the impacts of various road conditions (e.g., slushy, icy, snow covered) on traffic speed and safety. To this end, an extensive literature review was conducted and it is found that over 30 studies have examined the impact of winter weather on traffic safety or vehicle speeds (e.g., *5-13*). Those past studies exhibit a wide variety of approaches and results. However, this study focuses on some of the studies that specifically examined the effects of pavement surface condition on safety and speed. As a result, the effects of various pavement surface conditions on safety and speed are quantified by using adjustment factors, as shown in Table 3. For more details regarding the determination of adjustment factors, refer to the study by Strong et al. (*14*). It is assumed that both the safety and speed adjustment factors under "Dry"

TABLE 3 Traffic Safety and Speed Adjustment Factors

LOS Condition	Crash Adjustment Factor (%)	Speed Adjustment Factor
Dry	100	1.00
Wet	150	0.96
Chemically Wet	150	0.96
Damp	100	1.00
Lightly Slushy	150	0.90
Slushy	175	0.87
Deep Slushy	200	0.84
Dusting of Snow	150	0.96
Frost	370	0.94
Lightly Icy	200	0.94
Icy	800	0.85
Very Icy	1600	0.83
Lightly Snowcovered	210	0.89
Snowcovered	870	0.84

pavement condition are equal to 1. Adjustment factors of other pavement conditions are developed based on the dry pavement condition. Moreover, for the purpose of travel time calculation, this methodology assumes that motorists will drive at the posted speed limit under dry pavement condition.

The output from MDSS simulation can be used to calculate the number of hours at which a route segment is operating at a given LOS (pavement surface condition). Thus, delay savings and safety benefits can be calculated based on the change of LOS between the control and MDSS scenarios (same condition and same resources).

Winter maintenance usage data (e.g., material costs, labor hours, equipment usage) can be used to validate if the simulated resource usage is in the reasonable range. Without this information, it is possible that the resource usage may be either overestimated or underestimated.

CASE STUDIES

Three case study states were chosen for BCA. These states represent different climatologically groups: a transition–freezing rain state (New Hampshire), a mountain–west state (Colorado), and a northern plains state (Minnesota). The BCA was conducted based on the assumption of statewide application of the PFS MDSS. The information of baseline data, simulation routes, and analysis results for each case study is described in this section. For detailed information, refer to the report (*15*).

Baseline Data

As indicated in Figure 2, a variety of data are required to develop the baseline data module. The collected data and associated analysis results for the case studies are summarized as follows:

- Road data. A global information system shapefile that stores state highway information was obtained each case study state. The shapefile records highway segment information such as name of the highway, start and end mileposts, speed limit, and average annual daily traffic (AADT). After data processing, the number of route segments and centerline miles are 723 routes and 3,300 mi for New Hampshire; 889 routes and 11,839 mi for Minnesota; and 613 routes and 9,057 mi for Colorado.
- Crash data. In the baseline data module, it is required to identify the number of crashes on route segments. To support this, several winter seasons (November 1 of one year to March 31 of the following year) of crash data were gathered to determine the number of crashes on each segment. For simplicity, the average number of crashes during the seven winter seasons was used to estimate an average crash rate, without considering any effects of changing traffic volumes on crash rates in a given year. The total numbers of crashes by crash types (property damage only, injuries, and fatalities) were also calculated so that the average cost of crashes can be calculated for the whole state, given motor vehicle accident costs for different crash types (*16*).
- Traffic volume data. Given the speed adjustment factors, the analysis of delay benefits should also have traffic volume data. Vehicle traffic volumes will vary throughout the day, and will also vary from weekdays to weekends. In the absence of hourly traffic volume counts for each route segment, it was assumed that winter storm events may occur at equal frequency at any time of the day and that winter storm events are equally likely to occur on any day of the week. If the timing of storm events is uniformly distributed like this, then this allows one to assume that traffic volumes are evenly distributed throughout the day. This means that the AADT volume can be used to determine hourly traffic volumes.

  Seasonal adjustment factors were calculated based on an examination of monthly traffic variation at automatic traffic recorder sites. The general process was to take a 12-month period, calculate the average daily traffic volume in the winter months (November through March), and divide it by the average daily traffic over the entire 12-month period. This generated a seasonal adjustment factor for each site. The seasonal adjustment factors for all valid sites (i.e., all sites with at least one 12-month July-to-June period with no missing observations) were averaged, resulting in statewide seasonal adjustment factors of 0.913 (New Hampshire), 0.919 (Minnesota), and 0.891 (Colorado).
- Weather data. Historical weather data were collected from the National Weather Service's National Climate Data Center database (*17*). Hourly weather data over the past three decades from 107 weather stations (13 in New Hampshire, 61 in Minnesota, and 33 in Colorado) were obtained and only winter season data were used for developing the baseline data module. Those winter seasons missing more than 25% of the hourly observations were excluded, leaving 1435 seasons of winter weather data from 102 weather stations. Approximately 35,000 storm events were identified based on the parameters in Table 2. The *k*-means cluster analysis method was then applied to group the storm events into 20 storm types. It was assumed that the weather for a given route segment was the same as at the closest weather station. Finally, the number of each type of storm per winter season for each route segment was assigned to the baseline data

module. For benefit analysis, it is assumed that the climate (in terms of storm frequency and storm type) did not have significant change during the last decades.

- Statewide material usage data. As requested from the three state DOTs, the statewide material usages are: 152,653 tons of salt for New Hampshire during the winter season of 2006–2007; 234,629 tons of salt for Minnesota during the 2007–2008 winter season; and 111,622 tons of ice slicer for Colorado during the 2006–2007 winter season. A variety of materials were used in Colorado such as ice slicer, salt, and deicer. All the materials were converted to equivalent ice slicer based on eutectic properties of different materials. The material usage information is used for comparisons with simulation results.

Simulation Routes

Brief information of simulation routes in each state is described as follows:

- New Hampshire: A 9-mi highway segment on I-93 from Manchester to the Massachusetts state line (milepost 11 to 20) was simulated over seven consecutive winter seasons (1998–1999 through 2004–2005).
- Minnesota: A Supercommuter route segment on I-94 (within the St. Cloud County) was selected for simulation. A course of five winter seasons (from 2001–2002 to 2005–2006) was simulated for this highway segment.
- Colorado: A highway segment on I-225 was used for MDSS simulation. The length of this segment is 12 mi from milepost of 0.00 to milepost 12.00, basically running through Aurora, Colorado. Four winter seasons of winter maintenance from 2004–2005 to 2007–2008 were simulated for this route.

Costs and Benefits

For each case, the calculation of tangible costs included five aspects: software and operations costs, in-vehicle computer hardware investment (e.g., MDC), communications costs, training cost, and administrative costs (including support from agency information technology staff, e.g., route configuration, call-in technical support). It should be noted that the costs did not include weather forecast provider costs, since states that do not use MDSS also purchase weather forecast services for winter maintenance.

The benefits and costs of case studies are presented in Table 4. The results show that the use of MDSS for winter maintenance could bring more benefits than costs. However, the benefit–cost ratios vary with cases: 2.25–7.11 for the same condition scenario and 1.33–8.67 for the same resources scenario. For the same condition scenario, it is found that the contributions of user benefits to total benefits are almost the same as agency benefits for all cases. The splits of benefits for the same resources scenario, however, have large variations. In the Minnesota case, the same resources scenario used much more salt (12.7% of total usage) than the base case for winter maintenance and seemed to deviate more from the assumed same resources point 2 (in Figure 1) than the other two cases; the additional use of salt did improve motorist safety and mobility, but the total benefits were reduced. By comparing benefit–cost ratios, the same condition scenario tends to produce similar or better results than the same resources scenario.

The total resource usages of the control scenario were very close to the actual resource usages. The absolute errors of the simulated values are approximately 2% (New Hampshire), 5%

TABLE 4 Summary of BCA

Case State	Scenario	Benefits	User Savings (%)	Agency Savings (%)	Costs	Actual Resource Usage (ton)	Simulated Resource Usage* (ton)	B/C Ratio
New Hampshire	Same condition	$2,367,409	50	50	$332,879	152,653	149,980	7.11
	Same resources	$2,884,904	99	1				8.67
Minnesota	Same condition	$3,179,828	51	49	$496,952	234,629	222,968	6.40
	Same resources	$1,369,035	187	–87				2.75
Colorado	Same condition	$3,367,810	49	51	$1,497,985	111,622	107,091	2.25
	Same resources	$1,985,069	90	10				1.33

NOTE: * The total resource usage in the control scenario (base case).

(Minnesota), and 4% (Colorado). The small errors implied a good consistency between simulation and real-world data.

DISCUSSION OF FINDINGS

The feasibility of such a simulation-based approach depends on the validation of the MDSS in its ability to accurately simulate the future pavement condition resulting from weather and maintenance. As a part of its development of the pooled-fund MDSS, Meridian undertook several case studies to see how accurately the software predicted pavement conditions during various storm events (*18*). Though the predictive accuracy of MDSS was tested only within the range of these case studies, the case studies collectively represent a diversity of weather conditions and winter maintenance treatments. Consequently, though more validation of MDSS's predictive accuracy is necessary, the authors believe that the simulation results are sufficiently accurate to highlight the relative scale of benefits that might be realized through MDSS implementation.

This analysis included only selected tangible benefits and costs. As mentioned earlier, this methodology does not include potential agency savings in labor and equipment usage, as well as potential societal impacts. Case study results show that the use of MDSS is able to reduce materials usage (under the same condition scenario), reduce delay, and improve safety. The savings of labor and equipment costs are expected to be positive with reduced materials usage. The reduced usage of road salts for snow and ice control should also reduce degradation of the surrounding environment, corrosion effects on motor vehicles, and infrastructure damage. In addition, reductions in delay will result in reduced fuel consumption and greenhouse gas emissions. Other intangible benefits of MDSS include having an automated vehicle location platform to help with other data needs, helping in overall training of winter maintenance personnel, facilitating the paradigm shift to more proactive practices for winter maintenance, etc.

The number of storm types defined could have impacts on the BCA. For example, if a small number (*k*) of storm types are used, a storm type could include a large amount of storm events (with different parameter vector values); it may not be reasonable to assign the same resource usage for all the storm events within this storm type. If the *k* value is large, it is highly possible that some storm types will include only few storm events (or even zero) and this will affect the accuracy of resource usage for storm types and the number of hours under different pavement surface conditions. Further research may be conducted to evaluate the effects.

In the methodology, the weather data (dataset 1) used for step 5 in the baseline data module and those (dataset 2) used for simulation are different (e.g., the number of winter seasons covered). Thus, it is possible that the frequency of a certain storm type in dataset 1 may have significant difference from the frequency in dataset 2. However, it is assumed that they have negligible differences if enough weather data are gathered for analysis.

CONCLUSIONS

This study presented three case study results of BCA of the pooled-fund MDSS. The benefits and costs associated with MDSS, the base case and alternatives for BCA, and the benefit–cost model were presented. The analysis results are encouraging for agencies to explore the pooled-fund MDSS. It is anticipated that improving the level of user acceptance of MDSS and thus increasing the usage of the MDSS recommendations will lead to more benefits to be achieved.

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MANAGEMENT ASPECTS OF WINTER SERVICES

Integrating Maintenance Management Systems with Maintenance Decision Support Systems

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During the last decade, many maintenance managers have had the opportunity to work with increasingly sophisticated software systems which assists in keeping track of assets, tracking funding, and making day-to-day maintenance decisions. Two systems in particular are changing maintenance practices by increasing efficiencies and providing new insight into operational planning: maintenance management systems (MMS) and the maintenance decision support system (MDSS). Both MMS and MDSS provide maintenance managers with tools and technologies to maintain a safe and efficient transportation system. MMS sets performance targets, measures outcomes in times of limited budgets, and provides recommendations for tasks with competing needs. MMS now serves as a critical planning and management tool for public agencies, aiding in mid- and long-term maintenance decision making. On the other hand, the MDSS focuses on real-time maintenance decision making, providing decision support for winter maintenance activities. It uses weather forecasts and other data to generate recommendations based upon specific routes and customized rules of practice surrounding maintenance activities. Output from MDSS is used to optimize day-to-day and hour-to-hour anti-icing or deicing operations in winter. And while the current focus of MDSS is on winter maintenance, efforts are underway to expand its functionality to support nonwinter maintenance activities, e.g., determining when it's best to do crack sealing. For MMS to be effective, it relies on the input of high-quality data on expended resources, materials, and equipment in order to generate completed work activities and budget forecast reports. Such data entry is very time intensive for maintenance personnel, is needed while maintenance personnel are in the midst of fighting a storm, and is prone to errors. Similarly, for MDSS to be effective it needs up-to-date, near-term maintenance needs (i.e., data on the immediate maintenance actions to be taken and their location). Since such data inputs are often the output of the other system, integrating the two systems would minimize time demands for data entry, enable staff to focus on storm fighting, reduce data transfer errors, and lead to improved output from each of the systems. Such results will apply to the whole before–during–after timeline of snow fighting, and will ultimately improve and optimize the efficiency of existing maintenance resources and practices. This paper explores the benefits that may be gained by integrating these two systems, and the technical steps necessary to achieve this integration, building upon the strengths and capabilities of each.

The practice of snow fighting is far more complex than simply pushing a blade over snow-covered roads. Today, transportation agencies are faced with increased traffic congestion and elevated expectations from drivers while also facing tightening budgets, environmental regulations, and the political reality that the ability to travel on the road network really determines how severe a snowstorm is perceived to be. Winter maintenance personnel need accurate and route-specific weather and pavement forecasts to maintain a safe level of service (LOS) on roads. At the same time, they must also have an accurate picture of available storm fighting resources in terms of available labor, equipment, and materials.

Two complementary technologies currently exist that can provide better information for winter maintenance decision making. These are the maintenance decision support system (MDSS) and the maintenance management system (MMS). The MDSS combines route-specific atmospheric and pavement forecasts with winter maintenance rules of practice to generate optimized treatment recommendations tailored to agency requirements. The MMS is a tool designed to aid in decision making on maintenance-related work accomplishments, work prioritization, budgeting, and performance evaluation. This paper focuses on the strengths of each tool and how combining their capabilities improve data organization, operations management, and, ultimately, safety and mobility on the nation's roads.

MAINTENANCE MANAGEMENT SYSTEMS

In these times of reduced revenues and decreased highway infrastructure spending, MMS plays a critical role in helping agencies provide sound fiscal management of maintenance programs. This system provides access to maintenance data and allows for planning, organizing, directing, and controlling maintenance activity efforts. However, populating and maintaining a MMS is no easy task as the system can be very data intensive, requiring significant amounts of information in order to produce useful results.

For example, at the end of each maintenance shift, each crew member would enter input data into the MMS. This input data might include information on labor, equipment, and material costs for each task performed over that shift. The stored data can then be queried and presented in a report that compares input categories across a wide array of work accomplishments and completed tasks. Supervisors, managers, and administrators throughout the agency can then generate reports based on the desired information needed (e.g., 5-year average of salt and sand use on a specific 10-mi stretch of Interstate 80). This is an extremely important tool that can be used to help with resource planning, maintenance scheduling, resource allocation, preparing budgets, conducting performance evaluations, developing maintenance training programs, and providing necessary support for legislative requests.

MMS Capabilities

A well-maintained MMS can become a key decision-making tool for transportation agencies that are responsible for keeping roads open during adverse winter weather. The MMS can be effectively used for planning maintenance actions by aiding in defining overall objectives, work priorities, and procedures. By monitoring available resources, MMS can help in developing work programs and budgets, establishing LOS for specific routes, and defining the needed resources to reach these goals.

A MMS can be an aid in helping to organize the allocation of labor, material, and equipment resources. The system can assist in authorizing, scheduling, and evaluating maintenance-related projects as well as provide reports on project accomplishments, unit costs, and providing the needed information to recommend refinements in maintenance operations.

MMS Data Needs

As mentioned in the introduction, the MMS is a complex database that requires significant data input in order to receive benefits from the system (Figure 1). The input data could include the names of personnel who were assigned to a project, where the work was performed, what material and equipment was used, the nature of the activity, and ultimately what was accomplished. The following list provides some examples of input data for a typical maintenance-related MMS:

- Assigned crew member names;
- Hours worked (regular and overtime);
- Activity description (e.g., anti-icing in I-80);
- Agency assigned activity number (e.g., activity number 32 = anti-icing);
- Labor costs;
- Crew size;
- Equipment used (e.g., vehicle tag number, hours, mileage, and description);
- Material used (e.g., description, unit, amount used);
- Accomplishment (e.g., 10 mi of salt brine applied);
- Activity date;
- District or county route number; and
- Location and special instructions.

The more powerful MMS provide a very flexible reporting system, depending on the information desired and who requested the information. For example, in addition to project work scheduling, the MMS can be used as a powerful planning tool for budgeting labor, equipment, and materials based on the estimated work effort for a specific project or for an accumulation of planned efforts for a fiscal year. In addition, output from MMS can be used to

- Show work accomplished to support the department's budget requests to the legislature;
- Provide a crew-by-crew comparison of LOS and infrastructure maintenance;
- Illustrate comparisons of maintenance activities performed by contractors or state personnel;
- Help to identify sections of road which may qualify for rehabilitation; and
- Generate a comparison of projected versus actual material and labor expenditures for individual crews or projects or for entire districts of budget cycles.

MMS Benefits

A well-populated and maintained MMS can provide many benefits to transportation agencies such as allowing the generation of a diverse set of reports which can then be electronically shared across the organization. It allows for much more effective monitoring and control of materials, it eliminates duplicate data entries and can make the identification of erroneous data entries more apparent. For end users, the system does away with the overhead of recreating

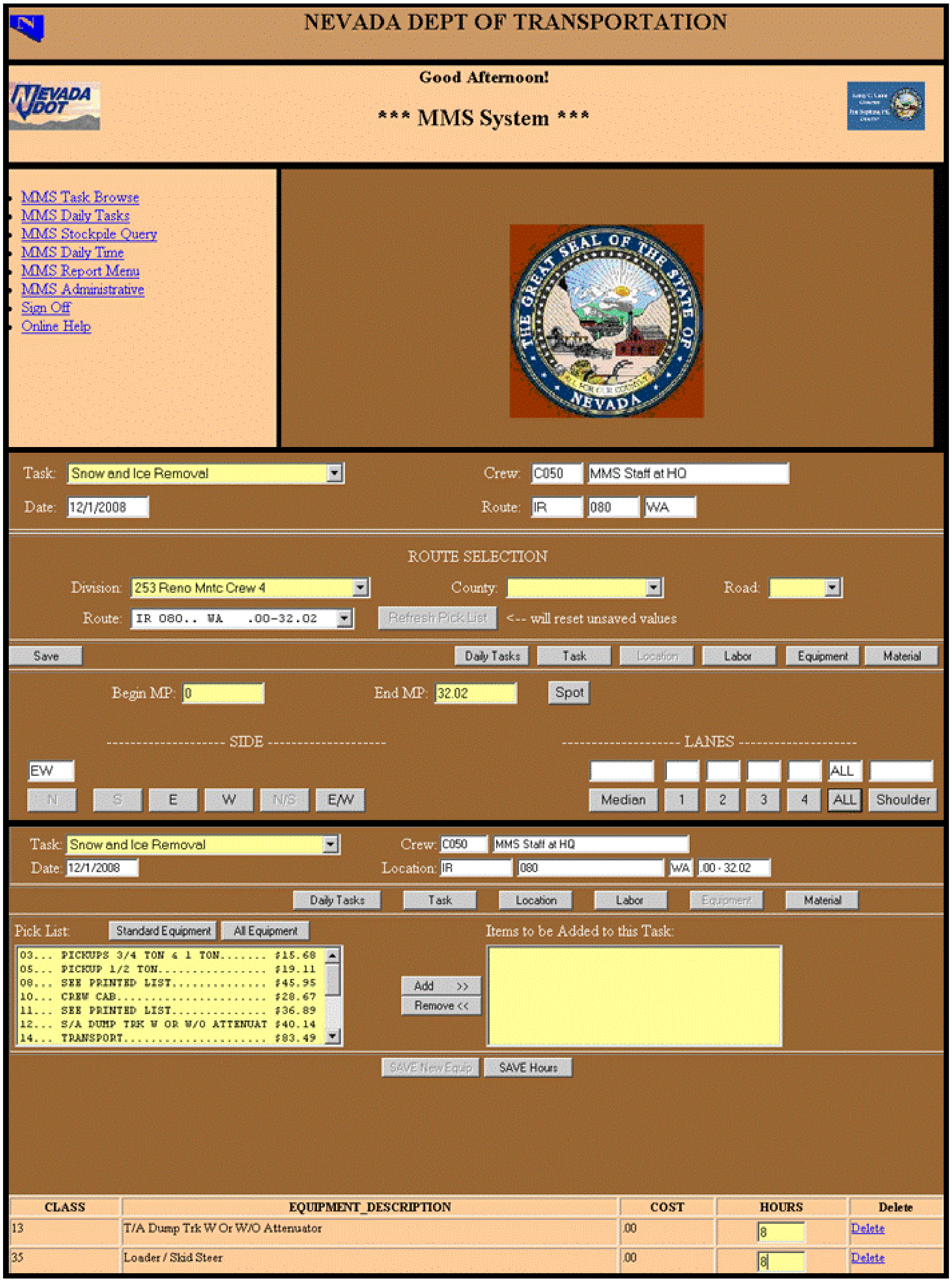

FIGURE 1 Example of the MMS interface used at the Nevada Department of Transportation. The top third of the image shows the MMS welcome screen with the listing of available MMS functions shown on the left. The center third of the image shows a task data input page. In this example, the task involves assigning a crew to perform snow and ice removal near the City of Reno. The lower third of the image shows how a maintenance administrator would select equipment (and their associated costs) for the assigned task.

information that has already been collected and can put diverse program details into the hands of maintenance personnel almost immediately.

The MMS can also greatly aid in project management such as coordinating large projects involving multiple crews and numerous pieces of equipment. The system can show the location of maintenance equipment and who was using it. Understanding these details can better enable central offices to justify the need for additional resources.

With respect to budgets, a MMS can provide a report on the LOS throughout the entire highway system, and how that may compare with overall funding goals. The MMS can also be invaluable for tracking contract maintenance costs and comparing contractor versus agency unit costs.

MAINTENANCE DECISION SUPPORT SYSTEM

The idea for a federal MDSS prototype began in 1999 out of the realization that public departments of transportation (DOTs) were not receiving optimal benefit from generalized weather forecasts and from roadway weather information systems (RWIS) that were available at the time. In order to make informed decisions about winter maintenance treatments, the forecasts had to become focused on road segments, and had to incorporate the operational actions of the DOTs. It is this linkage that would allow transportation agencies to improve their maintenance level of service, which would translate to a safer road environment and improved mobility. In today's environment of severely constrained budgets, this becomes all the more important.

Generalized weather forecasts can create significant challenges for DOT maintenance managers. For example, a forecast of "50% chance of rain, sleet, or snow developing; temperatures 30 to 35" does not provide sufficient detail so that maintenance managers can derive a sound mitigation strategy. Some key elements absent from this forecast include:

- Time of precipitation onset. When will the precipitation begin?
- Precipitation duration. How long will the event last?
- Precipitation probability. Is a 50% precipitation probability significant? Does it equate to a coin flip? How much confidence is in this forecast? Does it justify the cost in deploying resources?
- Precipitation type. Is there any better way to define the precipitation type?
- Temperature range. The forecast temperature range of 30° to 35° crosses several critical thresholds for mitigation strategies.

Finally, this forecast contains information only for atmospheric phenomena. There is no linkage to the pavement surface. Freezing or frozen precipitation may harmlessly melt if pavement temperatures are well above freezing.

Over the last several decades, public transportation agencies have deployed environmental sensor stations (ESS) as part of their RWIS strategy. These stations provide near real-time data on both atmospheric and pavement conditions. The benefits of ESS include the following.

- Observations are taken along DOT maintenance routes (versus at airports) and therefore provide important first-hand details about weather and road conditions, especially in known transportation trouble spots.
- Observations of both pavement and subsurface conditions are also typically available which are extremely valuable for determining precipitation accumulation potential and temperature trends.
- ESS data can play a critical role in initializing models for weather and road temperature forecasts.

Regarding this last point, ESS observations have a very short shelf life, i.e., most valuable within an hour or less during critical weather conditions (though certainly valuable for other purposes beyond that time). To be able to plan a sound adverse winter weather mitigation strategy, maintenance managers require road weather forecasts with the needs of the DOTs clearly articulated.

MDSS Background

The MDSS is a complex amalgam of data, models, algorithms, and interactive graphics (Figure 2). The federal MDSS prototype was created utilizing a consortium of national laboratories, but was well grounded through the participation of a very engaged stakeholder community. From the very first stakeholder meeting, it was clear that DOT maintenance personnel did not want to Because of the complexity of an MDSS, it is unlikely that DOTs will actually own or operate a system. It is expected that weather service providers will operate MDSS and provide customized solutions to the DOT community.

The MDSS federal prototype uses a number of different inputs. For weather predictions, forecasts (such as air temperature, wind, and precipitation probabilities) from one or more numerical weather models are used. To initialize weather and pavement algorithms, observations from automated airport weather stations and DOT-owned ESS are used. There are numerous other elements that are required which are relatively permanent aspects of the infrastructure. Others are defined by the transportation departments and reflect policies and practices that are fairly stable. All of these elements are input into the system once, though they can be updated as necessary. This includes such data as

- Latitude–longitude defining plow routes;
- Makeup of the pavement surface;
- Makeup of the subsurface layers;
- Historic traffic volume information;
- Commuting pattern (rush hour) information;
- Anti-icing treatment strategies;
- Deicing treatment strategies (which includes details about prewetting, use of abrasives, or just plowing);
- Types of chemicals used;
- Amount of snow left on the road surface after treatment (e.g., a half inch);
- Local climate parameters; and
- Location of bridges.

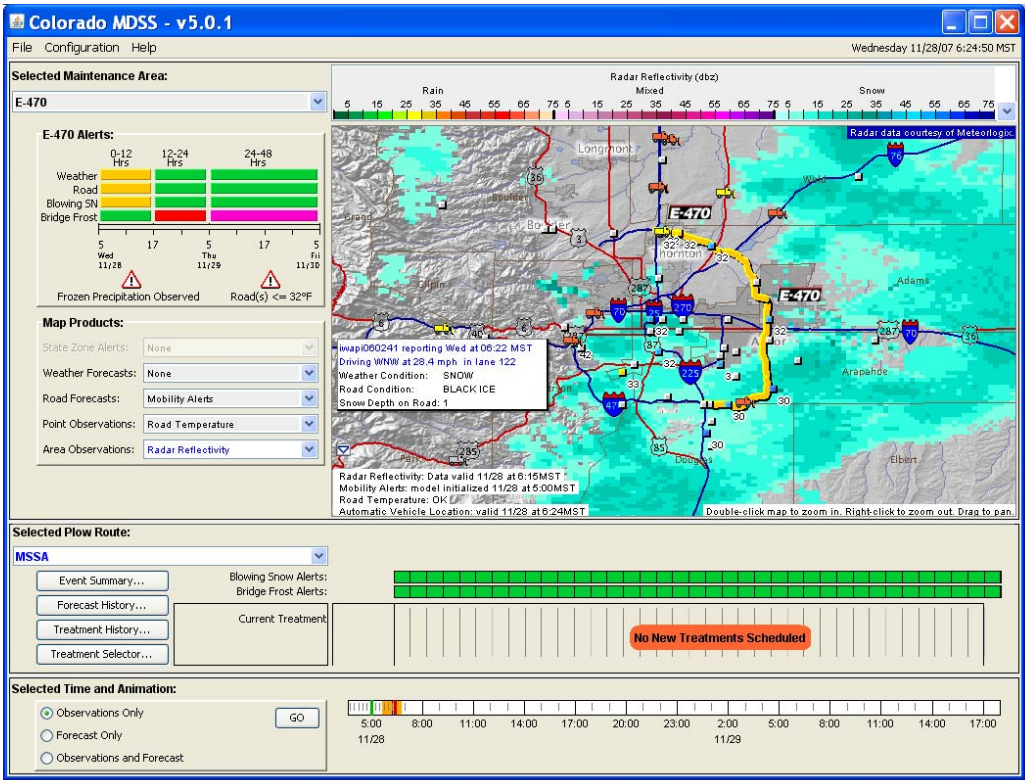

FIGURE 2 The MDSS federal prototype graphical user interface (GUI). The MDSS GUI was designed using input from maintenance personnel as well as visualization scientists. The GUI features a high resolution map (*top right*) showing maintenance routes, radar information (light blue patches) and forecast information (e.g., road temperatures). The GUI has an easy-to-read alerting section (*top left*) that uses colors to alert maintenance personnel of forecast adverse weather conditions, hazardous road conditions, or the potential for blowing snow or bridge frost. The GUI allows operators to display atmospheric and road forecast elements, ESS observations, and radar and satellite data. Treatment recommendations, event summaries, and treatment selections can be accessed through controls along the bottom.

Other inputs are continually changing, especially the weather observations and forecasts as described earlier, the treatment actions, the labor and equipment resources, and chemical stocks. These near real-time data inputs can come from a variety of sources, including MMS. Output from the MDSS is forwarded to a graphical user interface (GUI). The construction of the GUI was actively controlled by stakeholders to make sure that the information is presented in a format that is understood by DOT personnel. Careful use of visualization techniques has made understanding complex meteorological concepts visually intuitive. Figure 3 shows how forecasts of precipitation type (liquid, freezing, or frozen) are shown in an easy to understand graphic. Figure 4 provides an example of a computer-generated treatment recommendation. With these types of optimized guidance, maintenance decision makers have a much better understanding of the chances of each type of precipitation occurrence and how different maintenance strategies may impact mobility and safety on the roads.

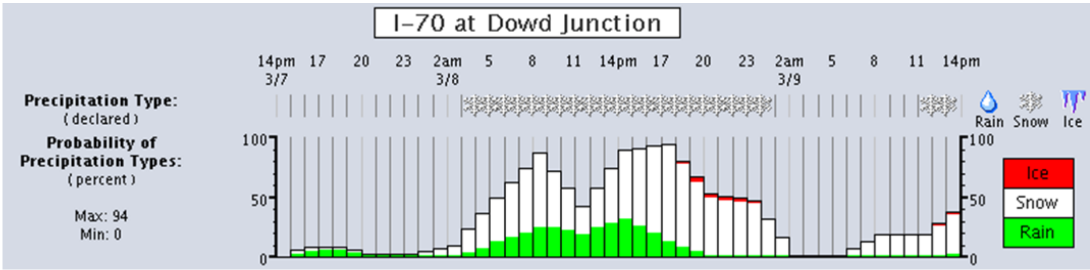

FIGURE 3 A portion of the MDSS event summary display, which is used to provide precise details about the forecast along a maintenance route (e.g., I-70 at Dowd Junction). Colors are used within the bar graph to show the probability of either ice (red), snow (white), or rain (green) will occur. The height of the bar shows the probability of any precipitation occurring each hour. The row of icons above the bar graph shows the expected precipitation type for each forecast hour (e.g., in this case, snowflakes).

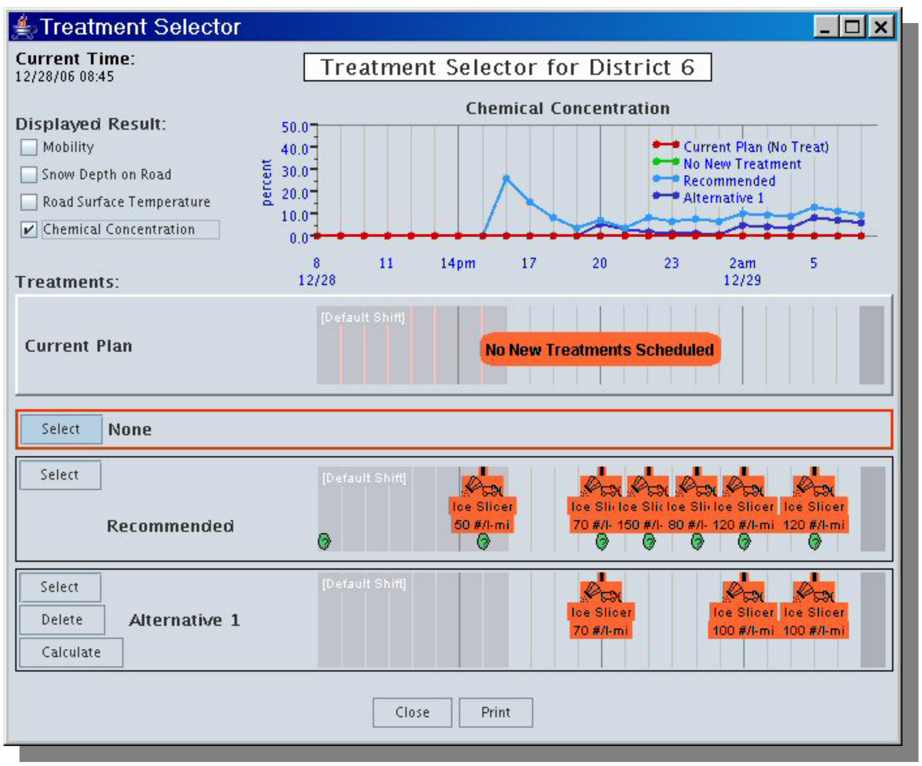

FIGURE 4 The treatment selector screen within the federal prototype MDSS provides the optimized treatment recommendation (shown as recommended) for a specific route. It also allows maintenance managers to change the recommendation to see how that might affect the outcome. In this example, an alternative treatment was entered (lower box listed as Alternative 1) which involves fewer chemical application runs and the distribution of less deicing chemical. The results are shown at the top where the chemical concentration percentage on the road surface is projected to be much lower than the recommended treatment. Maintenance personnel can use tools such as this to customize treatments according to their staffing, equipment, and LOS policies.

BRIDGING MMS AND MDSS

Separately, the MMS and MDSS provide valuable insight and act as tools for both the administrative and operational practices of transportation agencies. Each exhibits its own strengths and capabilities that are focused toward their individual functions. At present these two systems do not share or exchange data.

The ability to interconnect and allow for data exchange between the MMS and MDSS would benefit both systems. For example, the MMS could supply to the MDSS data such as:

- The types of snow–ice fighting chemicals in use;
- The supply and location of chemical stocks;
- The location of snow fighting equipment and their operational status (e.g., plows, supervisor trucks, sprayers, etc.); and
- Availability and number of maintenance crews.

Armed with these data, the MDSS would be better able to customize and optimize treatment recommendations associated with adverse winter weather. For example, the MDSS could provide information on the following.

- The location where precipitation will likely begin. This may allow maintenance managers to preposition equipment and materials close to where they will be needed first.
- The location where the heaviest precipitation is expected to fall. Equipment can be moved in advance to focus on the harshest conditions.
- The forecast timing of precipitation onset and duration. Economies can be realized if crews on not kept on standby for hours waiting for the event to begin.
- The ability to effectively anti-ice prior to the onset of a storm.

The recommendations from MDSS can be linked back to the MMS so that maintenance managers will be able to follow the deployment of chemical stocks, the use of labor and overtime, and the disposition and location of snow fighting equipment.

Enhanced Snow and Ice Control

MDSS capabilities continue to advance through the inclusion of new science (e.g., better forecasts and algorithms) and technology. One such technology that is being deployed by transportation agencies is associated with mobile data collection (MDC) and in particular the increased usage of Global Positioning System–Automatic Vehicle Location (GPS–AVL) technologies. Current GPS–AVL systems are capable of sensing and transmitting many data elements that are of great importance to both MDSS and MMS users. For example, GPS–AVL can collect data on

- Vehicle location and speed;
- Plow blade position;
- Distribution of chemicals and the application rate;
- External air temperature; and
- Pavement or surface temperature (using infrared sensors).

In addition to data collected automatically by onboard systems, many GPS–AVL units allow for vehicle operators to send in observations of weather and pavement conditions.

The ability to have MDC systems provide near real-time information to both the MMS and MDSS would be a tremendous advancement. Having real-world observations of weather and pavement conditions would allow the MDSS to generate more precise treatment recommendations which could be forwarded to the MMS. Having automated input of equipment location and chemical usage into MMS could be forwarded to the MDSS so that the system could further optimize plow route recommendations as well as understand what chemicals stocks were still available to treat the roads.

Beyond Snow and Ice Control

While the initial integration of MMS and MDSS has been focused on winter maintenance operations, the integration of these technologies could be effectively used year round to increase efficiencies, productivity, and crew safety for warm season maintenance projects. With the ability for MDSS to provide hourly forecasts of precipitation, managers would be better able to determine the risk of beginning activities such as lane striping. The pavement forecast capability would provide guidance on whether road temperatures would be in the proper range to perform chip sealing or patching. The wind forecast would alert managers if the direction and speed were within range to perform pesticide application and spraying. The ability to combine MDSS-provided weather forecasts and treatment recommendations with the knowledge of MMS would be a powerful new tool to use personnel and material resources economically.

CONCLUSION

Transportation agencies today have a number of sophisticated tools available to aid in decision making for fighting the adverse effects of winter weather on our nation's roads. Among them are the MMS and the MDSS. The MMS is a database that can contain data about equipment location and operational status, the amount of snow fighting chemicals in stock, and the availability of maintenance crews. The MDSS combines short-range weather forecasts with customized winter maintenance rules of practice to generate optimized treatment recommendations to maintain a desired LOS on roads.

Separately, these tools provide valuable decision-making support. However, by integrating their databases, it would allow maintenance managers the ability to compare the severity of an upcoming storm with available resource. It would provide better insight into the use of labor hours and potentially help in reducing costs by better positioning crews and equipment and cutting down on standby times. Exchanging data between systems—using MDC technologies for example—would reduce the time needed to manually enter data into an MMS, which would also reduce the likelihood of transcription errors. Finally, it provides transportation agencies with a tool that can be used well beyond snow fighting. This capability could be used year round to aid in project management during the warm season by scheduling projects according to weather risks. This could improve project completion rates, reduce the duration of work zones, and improve staff safety.

Use and Cost–Benefit of Weather Information in Winter Maintenance

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City of Oshkosh

Weather has broad and significant effects on the roadway system. Significant weather-related costs are also incurred by maintaining and operating the nation's highways. Weather observations and forecasts are important inputs for developing more effective and efficient treatment strategies in winter maintenance. Recent trends toward proactive winter maintenance operations have placed a premium on the value of timely and accurate weather information that reflects current and forecast conditions in the roadway environment. However, few studies have sought to quantify this value, and compare it to the costs of obtaining such customized weather information. For this reason, a project led by Iowa Department of Transportation, on behalf of the Aurora Program, seeks to evaluate benefits and costs associated with the use of weather information. This paper first summarizes weather information sources for winter roadway maintenance through nationwide surveys. Two case study states were then selected for evaluation purpose. The winter maintenance data during the 2006–2007 winter season were obtained from various maintenance units (e.g., cost center, crew) in these states. This paper applies the neural network and sensitivity analysis methods to model winter maintenance costs. The explanatory variables of the models include maintenance lane miles, level of service, weather severity index, frequency of weather use, accuracy of weather information (observations and forecasts), anti-icing, etc. Benefits of weather use are analyzed by using different scenarios, which have different frequency of weather use and different accuracy of weather information. Analysis results shows that the direct benefits of using weather information outweigh the costs

Weather has broad and significant effects on the roadway system (*1*). Adverse weather such as rain, snow, sleet, fog, and surface ice can impair the ability of drivers to operate their vehicles safely, reduce roadway capacity, and significantly affect the efficiency of roadway system. Significant weather-related costs are also incurred by maintaining and operating the nation's highways. State and local agencies spend more than $2 billion annually on snow- and ice-control operations (*1*).

Transportation agencies are under increasing pressure to maintain high levels of safety and mobility even during the winter months, while working with limited financial and staffing resources and recognizing the environmental challenges related to chemical and material usage (*2–4*). Due to the impact of weather on highway safety, a variety of programs (e.g., Aurora, Clear Roads, *Clarus*) have formed with the intent to improve the performance of the transportation system during inclement weather. The growing interest in weather information implies that such information could have significant value in helping meet the challenges of adverse weather on the roadway system.

Weather information may be gathered from a variety of sources such as free weather services, private-sector weather forecast services, roadway weather information systems (RWIS), public-sector weather services (or mesonets), and decision support systems (DSS). Each weather resource provides distinctive levels of detail in weather information. One trend among transportation agencies is to use sources that provide information more customized toward the roadway environment. This includes development of forecasts at a smaller geographic scale, in addition to focusing on weather at the road surface, where reduced pavement friction can adversely affect motorist safety and travel time.

The use of weather information is perceived to benefit winter maintenance in several ways (*5–7*). For example, weather observations and forecasts can help maintenance personnel respond to winter storms in a more timely and proactive manner; maintenance personnel will have better preparation for storms (e.g., better scheduling of material application, more accurate staffing, and reduced equipment usage). While it is perceived that winter maintenance costs may be reduced with more accurate weather information and higher frequency of usage, the magnitude of these effects needs to be explored.

Few studies have been conducted to quantify the benefits and costs associated with the use of weather information. SHRP conducted research regarding the potential benefits of improved weather information in the early 1990s (*6*). This pioneer research provided a comprehensive examination of RWIS at a time when RWIS implementation in the United States was not widespread. This innovative study used a simulation-driven computer program to estimate the cost effectiveness of RWIS. The simulation was seeded with a randomly selected, daily weather condition (the probability of which was supplied by user input), and then was run through a variety of arrays to estimate the benefit–cost (B/C) ratio and resulting service level. The model was run over a large number of runs so that the long-term frequency of a given weather event was equal to its input probability value. The simulation results indicated a potential B/C ratio of improved weather information of 5 to 1. Cost savings may result from a variety of factors, including reduced volumes of chemical or material usage and reduced staffing and equipment usage.

The SHRP study used many simplifying assumptions that render the model's conclusions less representative of current winter maintenance practices. For instance, the study assumed weather events change on a daily scale; weather events, as defined in the study, do not include considerations of temperature change through the event, which could affect treatment decisions. In addition to these simplifications, the model did not seem to be validated in this study. Though many of the assumptions and intervening data arrays appear logical and the conclusions regarding the cost effectiveness of improved weather information seem reasonable, it is unclear whether the model actually represents the field experience.

The objectives of this study are to (*a*) summarize weather information sources for winter roadway maintenance and (*b*) analysis benefits and costs of using weather information. A methodology of using neural networks and sensitivity analysis methods is proposed for analysis. The rest of this paper first summarizes the findings of weather information sources based on a nationwide survey to winter maintenance personnel. A general winter maintenance cost model is then introduced. Following this, a methodology integrating sensitivity analysis and neural network methods is proposed. Finally, two case studies are used to analyze and evaluate the benefits and costs associated with weather information.

WEATHER INFORMATION SOURCES

In 2007, a nationwide survey to winter maintenance personnel was conducted to learn about their use of weather information sources for winter maintenance, cost of weather information, and assessment of weather information. Totally 133 responses were collected from around 25 states in the United States and three provinces in Canada.

Although others sources were identified, this study focused on the investigation of five primary types of weather information sources: free sources, private-sector services, RWIS, mesonets, and DSS. The major findings from the survey are presented as follows.

- Among winter maintenance personnel, the most widely used sources are free weather information sources, private-sector weather providers, and RWIS. The other two sources, the road weather observation mesonets and DSS, have fewer users; they usually collect road and weather data from two or more sources such as National Weather Service (NWS) and RWIS, and fuse them to generate information of interest for winter maintenance. Private-sector weather providers, who act similarly to mesonets and DSS, collect weather data from NWS or other sources, ingest them, and provide specialized information of current weather conditions or forecasts. Thus, free weather information sources and RWIS are the two primary direct sources for collecting road weather information.
- The lack of cost and easy access contributes to the wide use of free weather information sources. However, these sources may have problems in timeliness and a lack of detail, which may result in use of inaccurate weather information. Based on the survey of winter maintenance professionals, the accuracy of weather sources is the biggest barrier of using weather information.
- Air temperature, wind, and precipitation amount and type are primary parameters of current and forecast weather conditions. Road weather elements such as pavement temperature, bridge temperature, and pavement conditions are also widely used for winter maintenance. In addition to these, winter maintenance personnel are highly concerned about the forecasts of the onset, ending, intensity, and duration of storm events. The importance of weather forecasts with different time scales decreases from nowcasts, short-, medium-, to long-term forecasts.
- One barrier to using private services and RWIS is the cost. For RWIS, the design and installation as well as the communications to RWIS are the highest cost components. Design and installation are one-time costs, however, and ongoing costs are perceived to be much smaller. The majority of the post-installation costs are spent in maintenance. From the survey, it is found that the percentage of winter maintenance budgets spent in obtaining weather information is relatively low (less than 1% or between 1% and 5%).
- The most noticeable benefit of using weather information for winter maintenance is reducing maintenance cost. The survey revealed that using weather information could save staffing, materials–chemicals, and equipment costs as perceived by maintenance managers, but lower percentages of field crews–supervisors indicated the reduction of maintenance cost. It is anticipated that through improving the accuracy of weather information, more money will be saved for winter maintenance. For RWIS, the benefits are not constrained to winter maintenance. State and local agencies are sharing weather data with a broader range of public and private users, who can also benefit from the deployment of RWIS.

Table 1 presents a summary of key attributes of the five major weather information sources highlighted in the winter maintenance personnel survey. The table uses several attributes such as target audience, extent of use, and cost, to make a comparison of them.

MODELING WINTER MAINTENANCE COSTS

In this study, winter maintenance costs refer to direct costs of materials, labor, and equipment. Indirect costs (e.g., societal costs) are excluded as they are difficult to quantify. The usage of materials, labor, and equipment can be affected by many factors; these factors are shown symbolically in Equation 1. The cost model is established at the maintenance unit (e.g., maintenance shed, maintenance garage, cost center, patrol yard) level, and the total winter maintenance costs are the sum of costs over all maintenance units within the state.

$$WMC_k = f(LM_k, LOS_k, WSI_k, WI_k, AI_k) \tag{1}$$

where

WMC_k = winter maintenance cost for the *k*th maintenance unit per winter season;
LM_k = lane miles of roadway maintained by the maintenance unit;
LOS_k = level of service of the roadways maintained by the maintenance unit, often characterized by the pavement condition;
WSI_k = winter severity index for the area managed by the maintenance unit;
WI_k = weather information usage (frequency and accuracy) by the maintenance unit; and
AI_k = level of anti-icing used by the maintenance unit.

Each maintenance unit is responsible for one or more route segments. Considering that roadways are classified into different service levels (often characterized by the daily traffic volume, assuming *j* levels), *LM* is then a $1 \times j$ vector to indicate lane miles of each level, as shown in Equation 2. The lane mile of a route segment is the product of the segment length and the number of lanes.

$$LM_k = [\sum_1^k L_{1m} \times Ln_{1m}, \ldots, \sum_1^k L_{jm} \times Ln_{jm}] \tag{2}$$

where L_m is the length of the *m*th roadway segment and Ln_m represents the number of lanes on this segment. In the previous UDOT study (*8*), a VMT factor (vehicle miles traveled on the winter roadways maintained by a maintenance unit) was used. The calculation of VMT is based on annual average daily traffic (AADT) and length of highway segment. It is obvious that different service levels of highways have different levels of AADT and require different levels of maintenance, but the *LM* factor is more directly related to winter maintenance costs than VMT. This is because VMT is a contributing factor to maintenance but *LM* is the result of maintenance. However, in the case that *LM* information is not available, VMT can be used instead.

TABLE 1 Summary of Weather Information Resources

		Free Sources	Private Services	RWIS	Mesonets	DSS
Target Audience		• Public	• Maintenance Personnel • Public	• Maintenance Personnel • Public	• Maintenance Personnel • Public	• Maintenance Personnel
Timeframe		• Current conditions • Forecasts	• Current conditions • Forecasts	• Current conditions	• Current conditions	• Current conditions • Forecasts
Level of interpretation		Low	High	Low	Varies	High
Extent of Use		Wide	Wide	Wide	Moderate	Moderate
Most frequently used weather parameters (1)	Current weather conditions	• Precip. amount and type • Air temperature • Wind	• Precip. amount and type • Air temperature • Wind	• Pavement temperature • Air temperature • Wind • Precip. amount and type	• Precip. amount and type • Air temperature • Wind • Pavement temperature	• Precip. amount and type • Pavement temperature • Wind • Air temperature • Pavement condition
	Forecasts	• Precip. amount and type • Intensity and duration of the weather event • Timing/onset of the weather event • Exit timing of the weather event • Air temperature trends • Wind/blowing snow	• Precip. amount and type • Timing/onset of the weather event • Intensity and duration of the weather event • Exit timing of the weather event • Wind/blowing snow • Frost Forecasts • Air temperature trends	N/A	N/A	• Precip. amount and type • Intensity and duration of the weather event • Timing/onset of the weather event • Exit timing of the weather event • Pavement temperature trends • Air temperature trends • Bridge temperature • Frost Forecasts • Wind/blowing snow • Pavement condition
Level of Detail	Meteorological data	Regional	Regional or Site-specific (2)	Site-specific	Regional or Site-specific (2)	Regional or Site-specific (2)
	Road Conditions	N/A	Site-specific (3)	Site-specific	Site-specific (3)	Site-specific (3)
Timeliness		May have time lag	In time	In time	In time	In time
Cost		Free – Low	Low - Medium	Medium	Medium	Medium

(1) In order of popularity, mentioned by at least 60 percent of respondents
(2) Depending on which weather sources used.
(3) With information collected from road equipment.

LOS refers to the actual pavement condition with respect to accumulation of liquid or frozen precipitate. The calculation of *LOS* may vary from state to state. For example, in some states, *LOS* is the number of hours until near normal pavement condition is restored. In other states, *LOS* represents the number of reports for various maintenance conditions, referred to *LOM*—level of maintenance (*8*).

The severity of winter affects winter road maintenance. Obviously, winter weather severity varies from place to place. Currently, several indices may be used to measure winter weather severity (*8*). A commonly used *WSI* is the index proposed in the SHRP study (*6*). This index is calculated based on the mean daily snowfall, minimum and maximum temperatures averaged over the season. In addition, as will be described later in the case study, some states developed their own indices for winter maintenance.

WI refers to the degree to which a maintenance unit uses weather information. *WI* has two meanings for winter maintenance: one is the frequency of using weather information (observations and forecasts), and the other is the accuracy of weather information. Thus, *WI* can be a 1×2 vector indicating frequency and accuracy.

Anti-icing is a proactive treatment method for snow and ice on roads, which can be initiated before the weather event begins or just as the precipitation begins falling (i.e., just-in-time anti-icing). The use of anti-icing can affect winter maintenance costs. A study found that the application rates for anti-icing are typically three to five times lower than those used in deicing (*9*).

In addition to the input variables in Equation 1, other factors may also affect winter maintenance costs and need be added into the model if possible. Whatever variables are included in the model, it is necessary to identify the key factors that contribute to winter maintenance costs, as will be discussed in the following sections.

METHODOLOGY

The previously outlined cost model can provide a good framework to evaluate the effects of weather information on winter maintenance costs. Before the evaluation using the cost model, it is important to identify the factors–variables that have significant impacts on winter maintenance costs. Hence, a two-step research methodology is developed. In the first stage, a sensitivity analysis method is used to explore the effects of various input variables on the output (cost) based on trained networks (by using neural network method). This stage will determine what inputs should be included in the cost model. Those input variables that have negligible impacts will be removed from analysis. In the second stage, a neural network is used to model winter maintenance costs and evaluate the impacts of weather information, given that the weather information factor is not excluded in the first stage. Both the neural network and sensitivity analysis methods are introduced as follows.

Neural Networks

A neural network is a modeling technique to mimic the performance of a system based on observed behavior of neurons. Neural networks are in the borderline area of artificial intelligence and approximation algorithms. As shown in Figure 1, a widely used neural network consists of three layers: the input layer, the hidden layer, and the output layer. The neural network modeling

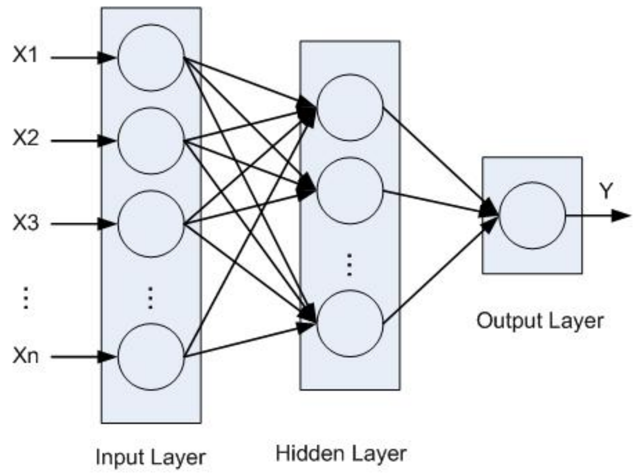

FIGURE 1 Architecture of the neural network model with one hidden layer.

is a dynamic and complex process that requires the determination of the internal structure and rules such as the number of hidden layers and neurons.

To date, there are numerous types of neural networks using different algorithms. Among them, the most popular network is the back-propagation neural network (BPNN) because of its simplicity and effectiveness (*10*). The BPNN accept inputs at the input layer and the inputs are summed with weights and passed to the hidden layer. Then, the sums in the hidden layer are weighted and passed to the output layer to generate the output. The back-propagation algorithm develops the input to output mapping by minimizing a mean square error function:

$$MSE = \frac{\sqrt{\sum_{i=1}^{n}(y_i - E(i))^2}}{n} \tag{3}$$

where n is the sample size of the training dataset, y_i is the model output (e.g., winter maintenance cost) related to the sample $i(i = 1, ..., n)$, and $E(i)$ is the estimated output.

Sensitivity Analysis

Sensitivity analysis is a method to study, qualitatively or quantitatively, how the uncertainty in the model output is attributed to different sources of variation (*11*). In this study, the objective of sensitivity analysis is to find the subset of input variables that are most responsible for variation in model output. In real-world applications, it is common that the sample size for network training is limited and the dataset includes many input variables, which may present challenges for appropriate training. Hence, it is important to reduce the number of inputs in the network model since some of the inputs may have negligible impacts (very low sensitivities), which in turn reduces the complexity of network and training time.

Before conducting sensitivity analysis, preparations need to be made. First, the input and output data are normalized. Normalization of data means that the parameters are scaled equally so that the sensitivities of input variables can be compared. Second, data from all normalized input variables are used to train the network. Sensitivity analysis is conducted based on the trained network.

To normalize the dataset, a minimum–maximum method was used. The min–max normalization preprocesses the network training set by normalizing the inputs and outputs so that they fall in the interval [–1, 1]. Through normalization, the input parameters are scaled equally. The min–max normalization can be realized through the following equation:

$$Pn = 2 \times (P - MinP \times OneQ)./((MaxP - MinP) \times OneQ) - 1 \tag{4}$$

where

P = a $R \times Q$ matrix of input (or output) vectors;
$MinP$ = a $R \times 1$ vector containing minimums for each P;
$MaxP$ = a $R \times 1$ vector containing maximums for each P;
$OneQ$ = a $1 \times Q$ vector containing 1s; and
Pn = a $R \times Q$ matrix of normalized input (or output) vectors.

It should be noted that in the normalization, a system (i.e., cost model in this study) is assumed $y = f(x_1, x_2, ..., x_n)$, where y is the output (or result) and $x_1, x_2, ...x_n$ denotes the inputs of the system.

Once the network is properly trained, sensitivity analysis can be realized through the following steps:

1. Estimate mean and standard deviation for each variable $x_i (i = 1, 2, ..., n)$.
2. For x_1, evenly divide the interval $[\bar{x}_1 - \sigma(x_1), \bar{x}_1 + \sigma(x_1)]$ (σ is the standard deviation) into *k* subintervals. Thus, there are *k+1* input values $x_1^1, x_1^2, ..., x_1^{k+1}$. *k=100* is used in this study, which means that the length of each interval (Δx_i) is less than $2/100 = 0.02$. It should be aware of the possibilities that $\bar{x}_1 - \sigma(x_1) < -1$ and $\bar{x}_1 + \sigma(x_1) > 1$, under which the input values outside the range of [–1, 1] will be excluded.
3. Calculate the results ($y_1^1, y_1^2, ..., y_1^{k+1}$) of the system for each element of the sample; other inputs are fixed at their respective means.
4. Analyze sensitivity of x_1 by using partial derivatives: $S_1 = {\partial y_1}/{\partial x_1}$, which is a $1 \times k$ vector. The calculation of sensitivity is approximated by the first order of the Taylor series (*12*):

$$S_1^i = \frac{\partial y_1^i}{\partial x_1^i} \approx \frac{y_1^i(x_i + \Delta x_i) - y_1^i(x_i)}{\Delta x_i} \text{ for each } i = 1, 2, ..., k+1 \tag{5}$$

where S_1^i is the sensitivity of x_1^i.

5. Calculate the average sensitivity (which is a positive value) for x_1: $S_1 = \left| \frac{1}{k} \sum_{i=1}^{k} S_1^i \right|$.
6. Repeat steps 1 through 4 for the rest of the input variables.
7. Obtain $S_1, S_2, ..., S_n$ for all input variables. Normalize the sensitivity values so that

$\sum_{j=1}^{n} \hat{S}_j = 1$, where $\hat{S}_j = S_j / \sum S$. The final sensitivity values are $\hat{S}_1, \hat{S}_2, ..., \hat{S}_n$. These values can then be used to analyze their relative importance in the output variable, and to select key factors for the system.

CASE STUDIES

This study uses data collected from the Iowa Department of Transportation (DOT) and Nevada DOT, two of the Aurora program (*13*) members, as case studies to analyze the benefits and costs associated with weather information. The brief descriptions of collected data and analysis results are presented in this section.

Study Data

To develop the cost model in Equation 1, winter maintenance records during the winter season of 2006–2007 were gathered from both state DOTs. The maintenance unit is referred to as a cost center in Iowa and crew in Nevada. Each cost center or crew was responsible for different route segments

For the Iowa case, the dataset included winter maintenance cost, lane miles, and winter weather severity index (WSI) for each cost center. The Nevada dataset included the information of winter maintenance cost and lane miles for each crew. Winter maintenance cost consisted of material, labor, and equipment costs. The total cost was used as the output variable (*WMC*) of the cost model. The WSI values in Nevada were calculated based on the method proposed in the SHRP study (*6*).

To develop the *LOS* variable in Equation 1, the number of hours until near normal pavement condition during each (maintenance) event was computed. The number of hours that a roadway segment operated under unacceptable pavement condition was calculated over the winter season.

State DOT maintenance personnel were surveyed to investigate the use of weather information and the level of anti-icing for winter maintenance. The survey was distributed to ask them about the frequency of weather information from various sources (e.g., roadside weather stations for weather observations, private-sector weather forecast providers), the accuracy of weather observations and forecasts compared to free weather services (e.g., NWS), the level of anti-icing, etc. Numerical scales were used to indicate qualitative data of frequency (1 ~ 4), accuracy (1 ~ 5), and level of anti-icing (1 ~ 5), as illustrated in Table 2

The survey was conducted for the winter season of 2007–2008; however, both state DOTs indicated that the use of weather information as well as the anti-icing level during this season was similar to that of 2006–2007. Thus, it is assumed that both the use of weather information and the level of anti-icing in a cost center did not change between these two winter seasons.

TABLE 2 Numerical Scales of Weather Information and Level of Anti-Icing

Values	Denotation of Numeric values		
	Frequency	Accuracy	Anti-Icing
1	Never	Much less accurate than free weather services (e.g., NWS)	Never
2	Less than daily, and only when storms are forecast or occurring	Less accurate	Interested in anti-icing but don't have the right equipment or chemical
3	Daily	Same	Interested in anti-icing but don't have good enough forecasts
4	More than once per day (more frequent when storms are forecast or occurring)	More accurate	Regularly employ anti-icing on selected routes
5	N/A	Much more accurate	Regularly employ anti-icing on all eligible routes

B/C Analysis Results

B/C analysis was used to quantify the effects of using weather information on the state's winter maintenance costs. It is an evaluation of the economic benefits and costs of a set of investment alternatives. To achieve this, three scenarios were developed.

- The base case assumes that the state does not purchase weather observations and forecasts for winter maintenance. This case does not mean that winter maintenance personnel will not use any weather information; they will likely access free weather services (e.g., TV, newspapers, radio). Under this case, it is assumed that all cost centers have the same frequency of using weather information, and is equal to 2 (less than daily, and only when storms are forecast or occurring) in Table 2; also, the accuracy of weather information is 3 with free weather service.
- Alternative 1 assumes that all cost centers are using weather information at their respective frequencies and accuracies. This represents real-world winter maintenance operations during the winter season of 2006–2007.
- Alternative 2 assumes that all cost centers are using weather information at their respect accuracy values, but all of them increase or keep their frequencies of using weather information to 4: more than once per day (more frequent when storms are forecast or occurring). This is to investigate the potential benefits of using more weather information under current accuracies.

During the analysis, the values of the variables other than frequency and accuracy were kept at their values in the original dataset. The frequency and accuracy were changed according to different scenarios. The results of B/C analysis are presented in Table 3. The direct benefits were calculated for the winter season of 2006–2007, while costs were yearly based. The weather information costs in Iowa include maintenance contract, private-sector weather forecast services, and other costs to cover nonwarranty issues such as vandalism, critter damage, and accidental damage; the costs in Nevada include RWIS maintenance cost and private-sector forecast costs.

Table 3 shows that the direct benefits of using weather information outweigh the costs, with a B/C ratio of 1.8 (Iowa) and 3.2 (Nevada), respectively. It is also found that given existing weather information accuracy, increasing the frequency of using weather information can bring more benefits to winter maintenance. The benefits of Alternative 2 over Alternative 1 are about \$281,000 (Iowa) and \$196,000 (Nevada).

The B/C analysis tends to be conservative because the calculation of direct benefits did not include all maintenance units. More benefits are expected when applying this evaluation method to all maintenance units within both states. Moreover, the B/C analysis only considered agency benefits and did not include benefits to motorists and society. The case study shows that the use of weather information is able to reduce resource usage, which in turn can reduce degradation of the surrounding environment, corrosion effects on motor vehicles, and infrastructure damage. In addition, it will benefit motorists with reduced delay and improved safety as the road surface returns to normal condition more quickly.

CONCLUSIONS

This study presented the key findings of weather information sources based a nationwide survey to winter maintenance personnel. This study also proposed a general approach for the modeling of winter maintenance costs. A methodology combining neural networks and sensitivity analysis methods was used to identify the key input variables that had significant effects on costs and to investigate how weather information affected winter maintenance costs. B/C analysis results of two case studies showed that weather information is a promising way to improve winter maintenance and reduced agency costs.

TABLE 3 B/C Analysis Results

Case State	Scenarios	Cost (\$000s)	Direct Benefits (\$000s)	Weather Information Costs (\$000s)	B/C Ratio
Iowa	Base	15,448	N/A	N/A	N/A
	Alternative 1	14,634	814	448	1.8
	Alternative 2	14,353	1,095	N/A	N/A
Nevada	Base	9,501	N/A	N/A	N/A
	Alternative 1	8,924	576	181	3.2
	Alternative 2	8,728	773	N/A	N/A

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Environmental Assets, Vegetation Inventory, and Maintenance Issues in Design and Construction

Management of Environmental Features and Assets

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State departments of transportation (DOTs) own or are responsible for thousands of valuable, unique, and sensitive environmental features—many constructed to comply with the Clean Water Act (CWA) permits, Endangered Species Act (ESA) consultations, Memoranda of Understanding with State Historic Preservation Offices for 106 compliance, National Environmental Policy Act of 1969 (NEPA), and many other environmental regulations. Examples include storm water management facilities, wetland replacement projects, stream restoration projects, reforestation projects, construction of sound walls, replacement of parklands, and wildlife crossing structures. Other environmental assets are maintained out of federal and state DOT environmental stewardship commitments or to comply with state laws or policies, such as control of invasive species on government property.

Typically, mitigation projects offset or replace a certain environmental function lost as a result of construction of the transportation project. In order for the environmental mitigation projects to continue to provide the long-term functionality intended when they were first constructed, they must be properly maintained, and when necessary, rehabilitated or reconstructed. These environmental mitigation projects may be considered as assets similar to other transportation features.

Adequate management of these environmental features impacts DOTs' ability to permit new projects and avoid process delay. When environmental staff sit down to discuss or negotiate mitigation with a resource or regulatory agency, the content and timing of what occurs is greatly affected by the resource agency's confidence in the DOT—that the mitigation they are discussing and what the DOT agrees to do will actually occur and that the features will be maintained to continue to provide the intended mitigation benefits into the future. Mitigation is negotiated and provided as a means to replace permanently lost functions of naturally occurring systems; resource agencies and the public depend on DOTs to follow through on implementation and maintenance of permanent mitigation to replace these needed functions. Without systems to support management of environmental mitigation features and interagency confidence from a demonstrated performance history, a DOT's work and interaction with partner agencies becomes much harder, more contentious, and subject to delay. DOTs risk legal violations, increased regulatory scrutiny combined with more rigid mitigation requirements, loss of public trust, and—for the DOT environmental specialists negotiating with other agencies—a loss of professional credibility.

Ideally, environmental staff and management levels of the organization would have information on DOT maintenance of environmental assets available for discussions with decision makers in other agencies and interested stakeholders, at the time of permitting decisions. In the absence of information, regulatory staff at other agencies often suspects that such maintenance does not occur. Such staff are familiar with the lack of comprehensive systems to protect and maintain mitigation features as regulatory agencies are often called on the scene during emergencies or severe failures—destruction of wetlands or right-of-way (ROW) habitat preserved for an endangered species—in the course of maintenance work.

The scope of the environmental asset management issue is large. A state DOT may manage in excess of 100,000 mitigation features, when all are tallied. A large number of these are culverts and other drainage or water quality features, for which some DOTs are beginning to develop condition assessment ratings and systems for prioritizing improvements. Other elements are newer to tracking or have been tracked more informally, if at all, through their life history. Life-cycle costs are rarely assessed and in the case of some environmental features, plans for long-term management are simply nonexistent.

METHODOLOGY AND FINDINGS

In fall 2008, we contacted over 100 individuals at the 50 state DOTs, plus the District of Columbia and Puerto Rico. Given the difficulty of addressing cross-disciplinary issues in areas that frequently fall through the cracks, due to lack of staffing and the nonregulatory nature of most maintenance, often five to eight individuals were involved before answers could be found regarding the DOTs' mechanisms for tracking and planning for maintenance activities for environmental features.

We found that very few statewide systems for maintenance of any environmental features were in place; however, DOTs had made the most progress in systems for vegetation management and culvert management. Vegetation management considerations were often supported by public visibility of roadsides and the emergence of integrated vegetation management (IVM), with attempts to increase the use of native species. Culvert management considerations have been driven by the age of the physical infrastructure and CWA requirements to identify and manage outfalls and water quality infrastructure such as sediment basins. CWA noncompliance carries a penalty and enforcement has increased in recent years; multimillion dollar consent decrees with the Environmental Protection Agency have become increasingly common. On the West Coast, other federal and state regulations have been drivers. Inventory, management, and retrofit of culverts to enhance fish passage for anadromous species such as salmon have emerged in part from listings under the federal ESA. Likewise, concerns for and improvement of ROW management practices, including reduced herbicide usage and correction of erosion problem areas, are also related to the protection of salmon.

The task of maintaining our transportation system and the associated environmental infrastructure is a complex and challenging job, made more so by staff cutbacks, shrinking budgets, and increased deterioration (maintenance backlog) coupled with increasing public expectations and accountability. In some cases, environmental infrastructure elements are reaching the end of their service lives. A significant number of highway culverts have now experienced service lives in excess of 35 years (*1*) To gain an appreciation for the scope of the issue for DOTs, while bridge assets, for example, are relatively few in number and follow a federally mandated inspection frequency, a typical DOT owns tens of thousands of culverts (*2*).

DOTs have made the most progress in inventorying culvert and drainage system elements; however, in most states, specified maintenance procedures are just beginning to be developed. Many state DOTs are still locating outfalls, incorporating as-built information, and working toward a complete statewide inventory with use of Global Positioning System (GPS) equipment to obtain precise latitude, longitude, and elevation coordinates for the outfalls they have in their inventories. A further step is condition assessment (rating systems and regular, reproducible surveys) and asset management. Of those in existence, Maryland State Highway Administration's (SHA) hydraulic system inventory is a national model. Maryland SHA's system includes field evaluations of all storm water management elements in the SHA's ROW, including photos, reproducible evaluations, as-built plans, maintenance schedules, and forecasts of projected water quality improvements from potential changes to investment and management strategies.

DOTs are making scattered progress on improving tracking and planning processes for other environmental features, often on a district-by-district basis. Condition assessment systems are still being developed and for the most part, there is no hard linkage to DOT asset management systems. Beyond culvert management, environmental features are evaluated at best, considered by a team, and recommendations are made to management for funding in the next or future planning cycles.

While maintenance requirements for wetlands are specified for the permit and inspection period, long-term maintenance responsibilities in perpetuity often are not. Instead, DOTs typically try to design such features to avoid maintenance requirements. If significant land management and off-ROW mitigation are involved, state departments of natural resources (DNRs) often assume management responsibilities. DOTs are evolving increased capability to identify and manage individual areas in the ROW, such as populations of rare plants, infestations of invasive species, and mitigation areas, as a subset or special category of other maintenance activities, which are typically underfunded. DOTs have limited funding for more planning and data intensive activities such as IVM and environmental management systems. Long-term maintenance requirements are rarely, if ever accounted for in long-range planning or project budgets, and there is no federal participation in this end of transportation, which can otherwise prompt such planning.

In all but a few states, communication of commitments through project development, construction, and all the way to maintenance is still a challenge and adequate systems are lacking (*3*) Interagency commitments and mitigation facility requirements have not always been effectively conveyed to maintenance or budgeted such that maintenance can manage the necessary work and additional burden. As of 2008, environmental commitment tracking systems developed by DOTs in a number of lead states have not yet been expanded to track maintenance of environmental features.

Maintenance Role at DOTs

Maintenance staff at state DOTs cover an incredibly broad range of services for the agency and essentially must become specialists in many areas. In addition to their other areas of technical knowledge and experience, DOT maintenance staff are now expected to increase their environmental knowledge as well, to better manage the resources the DOT oversees. For example, DOT maintenance staffs in Virginia are required to take a course in in-stream work and environmental best practices. New York State DOT offers both extensive classes on environmental aspects and environmental support staff, but few states approach this level and New York DOT still lacks effective asset management systems for green infrastructure (*4*).

Operations and maintenance are often the most resource-constrained divisions of a DOT. Maintenance needs typically overwhelm available resources. Even when a state is making progress mapping and assessing physical infrastructure elements like culverts—far surpassing asset management tools and resources for other environmental infrastructure, “the agency is (naturally) more concerned about the 5,000 culverts that need to be replaced” because they are falling apart than the many that are functioning to remove water from the road, but could use upgrades for fish or wildlife passage, as California DOT (Caltrans) has noted in the process of beginning to identify where culvert improvements are needed to improve fish passage (*5*). Despite the progress, the agency noted that their ability to conduct such evaluation has been hampered because environmental maintenance and retrofit often requires further design and hydraulic analysis, before prioritization and programming can occur. In almost every case, DOTs lack mechanisms to pay for or perform such analysis or environmental work in maintenance, making such work more difficult to execute.

Few States Have Policy Goals for Environmental Asset Management

The most common area for DOTs to have agency policy dealing with environmental asset management is in appearance or other standards for maintenance of roadside vegetation. In recent years, several states have begun publishing agency performance to standards and objectives in highly visible locations, even providing press releases or reports. For example, Washington State DOT produces a quarterly performance report called the *Gray Book*, published on the agency’s website, although most objectives are related to project delivery, the agency maintains some statewide environmental objectives related to environmental asset management, mainly related to management of roadside vegetation. Maryland SHA is one of the few states with a maintenance policy goal related to asset management beyond roadside appearance. Maryland SHA has a policy goal in their environmental strategic plan that calls for gradual achievement of functional adequacy for 95% of storm water management facilities by 2010. Organizational goals are reflected in business plans down through all levels of the organization. At North Carolina DOT, maintenance has set up a performance-based condition assessment system that encompasses hard environmental assets and sensitive vegetation areas, with statewide tiers, regional tier, and subregional tiers, and different levels of service. Each division sets goals and tracks performance in a database.

Lists of Environmental Assets and DOT Commitment Tracking Systems

Asset management for environmental features faces particular challenges; while signs, bridges, and pavements are supposed to look pretty similar across the country and may be evaluated to common measures environmental assets have a much broader range of variability. Lacking such systems and condition data, DOTs use a wide variety of methods to keep track of their environmental assets, ranging from the memory of environmental specialists and informal unwritten understandings between agencies, to lists and Excel spreadsheets on individual specialists’ desktops and to web-based comprehensive environmental information and decision support systems. Headquarters environmental specialists frequently develop stand-alone tracking methods for archaeological sites, wetland mitigation areas, wildlife crossings et al., that are focused on ensuring environmental commitments and mitigation features are tracked through at least the permit or formal consultation terms or provisions of the interagency memorandum of agreement; however, lists or spreadsheets kept by individual resource specialists can easily be lost when there is a turnover in staff.

Increasingly, some agencies are using GPS to track the location of environmental features, but incorporation of restrictions, obligations, or other information is less common. Typically, geographic information system (GIS) is used to capture, store, and manage the data but there is not a formal, integrated process to ensure complete sets of environmental information are entered into the system and to ensure maintenance staff have access to the information. In some cases, environmental staff has seen the need to develop mitigation document management systems, as in California's biomitigation database, but the complexity and specialization of the mitigation documents therein do not lend themselves to use by maintenance. The system has no connection to maintenance management systems (MMS).

For the vast majority of DOTs that don't have a formal MMS for environmental resources, individual environmental resource specialists try to pick up the slack, tracking and field checking the mitigation features or protected resources and working with maintenance staff to repair or restore them when needed. Resource agencies are typically out of the picture unless there is a complaint from the public; compliance rests with DOTs' commitment to environmental stewardship and doing the right thing.

A few DOTs have chosen to develop commitment and mitigation tracking mechanisms, generally using Excel or Access or in-house programmed systems. The handful of more formal statewide systems that DOTs have developed still fall short of tracking commitments that need to be executed post-construction and facilitating management of commitments by DOT maintenance staff, with or without support from environmental specialists. DOT commitment tracking systems extend to "the point where project delivery ends," as in Caltrans' case; they don't typically do hand-offs to maintenance—operations and management doesn't have a plentiful supply of funds" (*6*). Washington State DOT's system is more extensive than most and the agency is working to develop a feedback loop to confirm follow through on commitments; however, maintenance activities are on another system and are not linked to the environmental commitment system.

Performance Thresholds and Triggers for Maintenance Action

Most state DOTs indicated a need and a desire to do post-construction monitoring, but few have a mechanism in place to trigger any type of routine surveys and repairs, particularly in the absence of permit requirements such as wetland monitoring or erosion control. For example, in New Jersey, the permitting agencies determine the standards and performance thresholds for water quality, fish passages, stream corridor restorations, wildlife crossings, noxious weed control, and sensitive plant protection, when they are involved due to permitting issues; however, the DOT does not use discrete standards or performance measures when permits are not required or when permits are complete. Maintenance may occur only when a staff person in the field notices that something needs to be handled or is not functioning as intended, and notifies maintenance management.

"It Very Much Depends on What Is Written into the Agreement"

Maintenance requirements are usually negotiated at the time of permitting. Maintenance requirements for wetland mitigation range from 3 to 10 years, and standards can be quite stringent; for example maintenance of no more than 10% invasive–weed species has been a common requirement that has been particularly difficult. After regulatory monitoring obligations are complete, Virginia DOT reports that wetland–habitat mitigation parcels are only tracked in the state's ROW and utility management system.

For most permits and environmental mitigation features, the situation outlined by Connecticut DOT is typical: Most environmental assets are installed–constructed during projects and inspected upon completion. Some assets are required to be monitored for a set number of years following construction as defined in the permit or construction specifications. After this period, many of these assets are not maintained unless there is a problem (*7*).

In the absence of permit requirements, most states do not have an action forcing mechanism to monitor or maintain environmental assets; thus there is very little follow up. Once permit requirements are satisfied, condition assessments, standards or thresholds to trigger action are exceedingly rare for most environmental mitigation features. Caltrans developed a biomitigation tracking system for optional use by environmental specialists. It has document management abilities and is currently being converted from Microsoft Access to an on-line system; however the system has no connection to maintenance. Follow up in maintenance depends on individual environmental staff. Even in a relatively progressive state such as California with greater-than-average resources for environmental staff and analysis, systems for ongoing tracking of post-construction environmental commitments and conditions are lacking.

Triggers and Thresholds Are Being Developed for Storm Water Management Facilities in Some States

Caltrans and most states have better systems when it comes to culverts and storm water management facilities. Maryland SHA's system is the most evolved. Maryland has a duplicable (A–F) grade-based rating system for storm water management facilities and has developed an inventory, database, and photo record of all facilities statewide and their maintenance status. Those graded A or B are considered functionally adequate; a standard the agency aims to attain for 95% of facilities by 2010. The GIS, document management, inspection, and remediation planning–tracking system supports compliance, work planning, and public correspondence. It can perform queries within a graphic environment for individual structures–features and attributes, by watershed, other jurisdiction, or roadway contract, with models that assist in analyzing the effects of changes in storm water management practices.

Better Information and Decision Support Systems Simplify Special Management

Maintenance staffs have little training on management of environmental assets, which may require more specialized knowledge or information. Typical training classes on environmental matters pertain to herbicide application, mowing, salt application, and equipment calibration, and in-stream work. The most sophisticated DOT systems automate more of this or develop handy color-coded guides for what maintenance staff members need to do.

SOLUTIONS AND RECOMMENDATIONS

Faced with funding and staffing constraints and lacking adequate inventory, condition assessment, and management systems in most cases, DOTs are evolving a wide variety of mechanisms to help address the issue of maintaining environmental assets. DOTs start by trying to design to minimize the maintenance costs of environmental features.

Minimizing the Complexity of Maintenance Features

Realizing that pots of money are rarely available for specialized, long-term maintenance, many DOTs have pushed back on resource agency requests for ultra-urban BMPs with more complex and expensive maintenance regimes. In recent years, DOTs have funded research on the runoff pollutant filtration effectiveness of low-maintenance vegetated swales. New Jersey DOT was among those who noted that though the agency has purchased vactor trucks for vacuuming out some ultra-urban BMPs, they generally attempt to utilize low cost, low-maintenance items in construction. Likewise, DOTs try to design wetlands to be hydrologically self-sustaining, without human management of complicated water delivery systems. Wildlife crossings are designed for minimal or no management, outside of maintenance of lead-up fencing or instructions to maintenance staff not to inadvertently bury entrances in snow-plowing operations. Cultural resource markers are designed to withstand the elements and graffiti, and maintenance checks are often folded into maintenance of rest stops, picnic areas, and highway pull-offs.

Value Engineering Environmental Mitigation Features

DOTs are also beginning to explore value engineering (VE) of environmental mitigation features. Washington State DOT received an award for Most Value Added Proposal in Pre-Construction Engineering for a \$25 to \$75 Million Project for its evaluation of the best ways to control and treat storm water runoff from the highway connecting Washington's largest cities, I-405. Much of the original design relied on the use of traditional ultra-urban storm water treatment structures—massive vaults and treatment systems. The VE team explored more environmentally sustainable solutions to eliminate hard structures. The VE team's most value-added proposal involved the replacement of the vaults with a number of alternative treatment options, offering additional accepted cost advantages exceeding \$62 million in maintenance savings over the life cycle of the project.

In 2003, Washington State DOT received the National Award for Outstanding Innovative Value Engineering Achievements for the SR 509–I-5 Corridor Completion Project. The VE study reviewed the storm water and staging aspects of the project and included neighborhood representatives, local government, transit. and community colleges, in addition to Washington State DOT design and environmental staff. The project involved 16 drainage basins and fish habitat, at an initially projected cost of \$102 million. VE saved the project 38% of that cost, resulting in fewer storm water facilities to maintain and an 11-month reduction in the schedule (*8*).

Partnering with Resource Agencies and Organizations to Take Long-Term Custody and Maintenance of Wetlands and Off-System Conservation Areas

DOTs have also conserved resources and planned for more efficient management of environmental mitigation features by partnering with resource agencies and organizations. Over the past decade, DOTs have pioneered partnerships with watershed and conservation organizations and state resource agencies to target DOT mitigation investments and help these agencies achieve their conservation priorities. State and regional conservation funds financed through in lieu fees helped achieve objectives identified by watershed plans to improve water quality and restore wetlands where they fulfill multiple filtration and wildlife functions in the watershed. In many cases, species and habitat conservation investments have been likewise directed where they can protect viable populations and where better, long-term management is more likely. Such partnerships offer excellent examples of interagency cooperation for the public good and efficient use of public resources, by leveraging what each entity can do best.

This early coordination and careful targeting of mitigation investments also helps ensure that the mitigation that is produced is desirable to managing entities, so they are more likely to agree to assume mitigation responsibilities. DOTs from New Jersey to California report increasing awareness of the costs of such long-term mitigation responsibilities, and the need for maintenance endowments; however, states sometimes face administrative limitations in what they can commit to do. Caltrans, for example, can't promise the credit of the state to perform future maintenance activities itself; "if the agency decides they aren't doing it next year, they aren't doing it" (*9*). Staff say the better they are at estimating environmental costs, the more likely they are to be able to figure out a way to address the needs.

At Florida DOT, wetland mitigation is outsourced to water management districts. Florida DOT paid for wetland mitigation at a flat price of $75,000 per acre initially, escalating with the consumer price index up to around $100,000 per acre now. Species or habitat conservation areas are frequently deeded to the state game commission or other agencies with land management expertise. North Carolina DOT has outsourced its mitigation program and long-term management to the state department of environment and natural resources, where a new division manages long-term stewardship responsibilities and relationships with land trusts who assume mitigation maintenance responsibilities. Both North Carolina and Colorado have entered into partnerships with nongovernmental conservation organizations to manage conservation areas or easements in perpetuity. Over the last few years, North Carolina Department of Environment and Natural Resources has been mapping locations of wetland mitigation sites and designing a geodatabase (based in ArcHydro) to hold important GIS features for all its sites. GPS units running ArcPad network with the database help locate site features that are obscured by vegetation, mark easement boundaries, and record monitoring information. North Carolina DOT still maintains many mitigation sites within its ROW with maintenance issues similar to other states.

Meanwhile, DOTs have encountered difficulties in extending the adopt-a-highway model, even when free labor has been volunteered. For example, New Jersey DOT tried but was not able to begin an adopt-a-wetland program, whereby volunteers would clean out the wetlands and help do additional plantings. Agency staff was told that there would be liability issues. A deer club interested in helping to maintain deer fencing along a highway in Colorado was turned down for similar reasons. Even existing programs can be difficult to continue, without strong connections to DOT goals and priorities. In one state, the adopt-a-highway program was terminated due to lack of DOT staff interest in managing it.

Internal Systems and Outsourcing Environmental Asset Management

Asset management responsibilities for environmental features can be handled in-house or contracted out, as with mowing. Virginia DOT headquarters develops memorandums of agreement with districts for monitoring and maintenance of stream and wetland mitigation features, during the CWA Section 404 permit monitoring period. If a district fails to carry out its responsibilities, headquarters can contract the work out. Florida DOT incorporates roadside maintenance, including everything in the ROW, fence-to-fence in its maintenance contracts and inspections address performance in limited areas related to environmental asset management. Florida DOT's Highway Asset Management Contracts typically include the performance of traditional maintenance activities such as mowing, shoulder maintenance, and drainage system cleaning; some of these address environmental mitigation requirements. At New Jersey DOT, a non-project-specific contract for roadside rehabilitation enables New Jersey DOT to do general maintenance on landscaped features when such work cannot be accomplished with DOT maintenance forces.

The Texas DOT is currently investigating the use of performance-based specifications and contracts in roadside maintenance. The DOT anticipates the study will result in the development of the optimum scope of work for this type of contract (asset types, maintenance activities, etc.) and develop methods for assessing the initial qualifications and continuing performance of contractors. Texas DOT will develop an oversight methodology and prepare performance-based roadside maintenance specifications. The results of Texas DOT's study will likely be transferable to other agencies and bears continued tracking.

DOT Environmental Commitment Tracking into Maintenance

DOTs have developed commitment tracking systems out of commitments to environmental stewardship, improving compliance reliability, and demonstrating performance. If extended to interagency reporting, tracking systems may also function as a tool to build comfort levels within and across agencies and to operate within more efficient, trusting relationships, as Maryland SHA has found.

While DOTs have begun to develop systems to track commitments developed in planning and particularly in project development, permits, and NEPA documents so that those commitments are addressed in design and construction, the states with the most advanced commitment tracking systems (Virginia and Washington State) are just beginning to extend their systems to facilitate communication with a handoff to maintenance. Commitment tracking and tracking of environmental assets, to the extent they occur, usually take place in separate systems. Intersystem communication abilities are minimal at this point.

District of Columbia DOT Plans to Track Environmental Commitments in Maintenance

The District of Columbia DOT is among the most recent to design a plan for an environmental management system and the agency has distinctive plans to track performance of environmental commitments in maintenance. Overall, the agency has set a target of a 95% completion rate for environmental commitments and features as planned. Semiannual reviews are planned during construction, scoring a checklist of environmental commitments. The agency aims for a score of at least 95% on routine evaluations performed by project management–site staff and at least 90% on spot checks performed by environmental program (EP) staff. As a follow up where corrective action is needed, the agency set a target of 95% for follow through on corrective actions and 90% for preventive actions, to be reviewed quarterly. Finally and notably, environmental commitments on maintenance activities will also be evaluated, comparing those performed to those planned or scheduled, with a target of completing 95% of that which is scheduled (*10*)

How needed maintenance is to be identified, programmed, and scheduled is not addressed in the plan, though the plan lists as Key Elements of Operation and Maintenance (*11*):

- Develop maintenance plans and budgets that reflect environmental commitments and requirements;
- Maintain and monitor, as applicable, environmental features and requirements;
- Verify conformance;
- Take actions, as needed, to ensure conformance; and
- Provide environmental assistance and support.

As in many other DOTs, compliance will rely on spot checks performed by EP staff, presumably as they are available. The project manager and environmental staff are supposed to identify commitments and requirements to be monitored—requiring periodic examination or sampling (e.g., assessment of vegetation); or maintained—features (e.g., catch basins or sediment control ponds) that require ongoing maintenance to function as intended. At the same time, they will determine associated actions and schedules. However, the when and how are more vague. The project manager and environmental staff will conduct periodic assessments to evaluate and ensure day-to-day conformance and if needed, identify corrective and preventive actions to address findings and assign responsibility and schedule for actions. Assigned staff will implement corrective and preventive actions in accordance with an action schedule.

Implementation tools include an environmental evaluation form, sample commitments and requirements summary, and sample commitments and requirements fulfillment checklists. The commitments and requirements summary sheet includes the following maintenance stage actions:

- Description of maintenance required for the commitment;
- Maintenance unit informed of requirement; and
- Maintenance unit acknowledgement of receipt.

With regard to monitoring, District of Columbia DOT intends to track

- Description of monitoring required for the commitment;
- Designated unit/individual informed of commitment; and
- Designated unit or individual acknowledges receipt of commitment.

With regard to agency coordination, D.C. DOT will track the extent to which the regulatory agency is informed of a commitment as it is incorporated into design–construction documents and agency acknowledgement of completion of commitment as described.

Corrective Action Tracking Is Still Emerging as a System Function

Maryland SHA and Virginia DOT have fully fleshed out corrective action identification, tracking, notification, and follow-up as part of their environmental commitment tracking systems. Washington State DOT's tool offers open, closed, or on-hold status for a commitment and Maryland SHA's environmental toolkit for the agency's independent environmental monitors also has issues and status related to the commitment that includes documenting what happened or what was encountered in an inspection, who was there, and how SHA responded. This information is reported instantly and raises credibility with the public and resource agencies, as it is available to anyone who wants information on a potential noncompliance event. However, this functionality extends to monitoring on construction sites and does not extend to maintenance (though SHA maintains another system entirely dedicated to hydraulic system inspection and maintenance). SHA utilizes on-site independent environmental monitors to perform daily inspections as a matter of course on all construction projects.

Virginia develops a site risk assessment and decides upon an inspection schedule for every project, but inspections beyond the permit period are also not continued in maintenance. Virginia DOT's Comprehensive Environmental Data and Reporting (CEDAR) system does facilitate environmental review of maintenance actions when they occur in environmentally sensitive areas, such as wetlands. Virginia DOT's asset management system is moving toward integration with Virginia DOT's system for tracking environmental workflow and permitting (CEDAR) and also the agency's database for hydraulic features and monitoring. Currently all maintenance activities with environmental aspects are reviewed through CEDAR; however mitigation features such as wetlands are tracked by the natural resources group and through the agency's GIS. After regulatory monitoring obligations are complete, wetland/habitat mitigation parcels are only tracked in the state's ROW and utility management system.

No state fully tracks all commitments from inception to maintenance, documents that they have been met, and reports on agency performance and opportunity areas for improvement, but Virginia's and Washington State's DOT increasingly comprehensive systems are closing in on this objective. Several others have limited scopes of commitments tracked but know they want to do more, while others have no plans to do so; their systems are providing the functionality they sought or the obstacles to do more are too high.

The scope and reliability of commitment tracking is a special concern as the most functional and comprehensive commitment tracking will have commitments enter a standard process that ensures they are tracked and considered at all appropriate points in the life cycle of the roadway and ensures that checks and balances are in place to prompt or guarantee that right steps are taken at the right times. Tracking well in one part of the life cycle and then not in another falls short of the ultimate objective.

Becoming More Systematic and Accountable in How Environmental Work and Commitments Are Executed

DOTs are using these systems—commitment tracking systems and systems (often the same) for tracking their work and increasing communication—to become more systematic and accountable in how work is performed. Taking a more complete, encompassing view of commitments, to ensure that all are tracked, WSDOT's permit conditions commonly run up to 80 pages per project. WSDOT is using their commitment tracking system to make sure that every commitment is recorded, and now the agency is using the system to inform and bolster discussions with resource agencies on exactly what the DOT is being asked to do.

The tracking systems are often intended to contribute to environmental management systems, as in Texas, Virginia, and Washington. Maryland, Virginia, Texas, and Washington are leveraging their systems to a degree, to develop a common way and a standard specification for work requirements or inspections, enabling fewer provisions and better training–enforcement around standards for staff, contractors, inspectors, though such aspects have yet to extend to maintenance of environmental assets.

Systems Have Improved Communications Across Silos, Awareness of Costs

DOTs with commitment tracking systems report that designing, developing, implementing, and using the systems have improved communications among the sections. The greater the interaction across silos during each step in the life cycle of these systems results in benefits that go beyond the systems themselves as the needs and issues of the broader organization are addressed and incorporated. DOTs and their environmental departments are learning that an ongoing and sustained effort is needed and is rewarded with success in the form of greater effectiveness and functionality in the resulting systems. Greater attention has also been generated for the costs of maintaining environmental features.

To Maximize Effectiveness, Use of the System Should Be Mandatory

DOTs that allow optional usage of their systems or widely varying levels of use lack a complete set of commitments to monitor and environmental assets that must be managed. To maximize system effectiveness, use of the system should be mandatory and training should be provided regarding expected level of use (i.e., which commitments or all commitments to be recorded, rather than project managers use to record just those commitments they think they might forget.)

DOTs see the systems as supporting internal management and technical work tracking functions more than serving external purposes. Conversely, when external access is granted and others start to rely upon it, the quality and completeness of that data become more important than ever. In general, DOTs' plans for external accessibility are limited. Virginia and Washington State DOT are fostering a culture of publicly reporting performance, Washington through the agency's Gray Notebook. Washington is also trying to add more performance reporting functionality to its system. Virginia reports instances of construction environmental non-compliance on its public on-line performance dashboards. If a problem is noted twice and has not been fixed, it is recorded as a noncompliance; however, this functionality focuses on construction only.

To date, Maryland is the only state to have made their system accessible to resource agencies. SHA's environmental monitor (EM) toolkit was built in part to communicate directly with resource agencies, and the arrangement has greatly increased the corps and the state department of environment's (MDE) comfort level with SHA's responsiveness about and seriousness in tracking environmental non-compliance. SHA reports there is almost no response from the resource agencies when they can see–monitor with their own eyes, via the system, that SHA is handling its situations itself. At SHA, resource agency requests (corps and MDE), comments or questions can be made through the EM toolkit. This allows SHA the ability to immediately respond to their needs and ensure all parties involved are up-to-date on environmental failures. SHA is considering providing access to other agencies, consultants, contractors, and other project stakeholders as needed and limited by project; however, the EM toolkit has not been extended to maintenance monitoring of environmental features.

Asset Management in MMS

Maintenance management and related systems are increasingly addressing and incorporating environmental components. Some states are incorporating environmental elements in their asset management systems for the other physical features they maintain. For example, a culvert management system may incorporate tracking of debris removal and fish passage, as well as maintenance and the life cycle of the physical infrastructure asset. In the late 1990s Washington and Florida DOTs developed systems for categorizing and improving outfalls (*12*). In the case of Washington, assessing which projects provide the best return on investment in terms of environmental effectiveness and pollution reduction. Washington State DOT's system included a condition indexing methodology and support program that enables users to quickly evaluate and compare projects and generate benefit-cost ratios for projects (*13*).

DOT staff sometimes indicated that environmental features are part of their maintenance management systems; however, on further investigation, this can mean that the department maintains herbicide application data sheets, rather than any particular electronic work scheduling or tracking system. Inclusion of "special management areas" in MMS is one way DOTs have begun to incorporate maintenance of environmental assets into MMS.

Special Management Areas in MMS

Special management areas in a DOT's MMS or GIS can identify the need for more specific and environmentally beneficial maintenance action. Caltrans' integrated MMS has all known locations and maintenance requirements for sensitive areas in the ROW. Environmental staff provides support in interpreting needs. Oregon DOT's system addresses 6,000 mi of ROW near salmon streams, with environmental data largely collected through remote sensing.

The ability of maintenance staff to implement needed specialty management is greatly enhanced by smart systems. For example, Pennsylvania DOT has linked maintenance equipment to a web-based GIS application to assist Pennsylvania DOT's district roadside specialists in managing and coordinating herbicide spray activities along state highways. RoSA (roadside spray application) provides a centralized database for the maintenance and operations of the roadside IVM program. In addition to producing maps and reports, the system guides various spraying operations (tank mix, injection, and end result) and provides additional layers of information (water features, guide rail, government properties, and boundaries, etc.) for managing the roadside IVM program (*14*).

Oregon DOT's Designation of Special Management Areas

Oregon DOT has remotely surveyed and field checked roadside corridors for special management areas, which are color-coded for different maintenance treatments. Oregon DOT's Directive MA01-131 provides guidance to staff for designating and managing special management areas (SMA). SMAs are areas within Ohio DOT's ROW where there are sensitive natural or cultural resources. They are typically identified in coordination with resource agencies during project development and may require a modification to routine maintenance activities to protect the resource. The directive outlines the roles and responsibilities for designating and managing SMAs. Region environmental staff, the region environmental manager, district manager, the central geo/environmental section and the office of maintenance work together through a step-by-step process to develop methods to minimize impacts to the resource.

When a potential SMA is identified, the nature of the resource is verified and a determination is made whether maintenance activities negatively impact the site, and methods are developed to temporarily minimize impacts until further investigation is competed. Environmental staff gathers the following information and submit it to the region environmental manager:

- Third-party verification of the nature of the resource;
- Description of resource sustainability needs;
- Citation of relevant laws for protection of the resource;
- Maps or surveys to confirm the resource is in the ROW;
- Confirmation that management of the resource isn't already included in other documents;
- Description of the detrimental effects by routine maintenance;
- Description of reasonable and safe BMPs and process for implementation; and
- Input from the resource agencies, where appropriate.

Once the region environmental manager and the district manager agree the site should be designated as an SMA, they work with all stakeholders to develop a site management plan including monitoring and reporting requirements, a draft budget, and the necessary BMPs or modifications to maintenance activities. The region environmental management and the district manager make the determination on the suitability of the site for SMA status based on whether maintenance activities adversely affect the site, routine maintenance activities can be modified without compromising public safety and health, and routing maintenance activities negatively affect the site but cannot be modified without compromising public health and safety. The region environmental manager documents the decision and, if the site is designated as an SMA, the district manager works with the environmental staff to implement the required mitigation. The central geo–environmental section reviews known resource sites to ensure the SMA designation remains appropriate and maintains the statewide database of review decisions and agreements, monitoring reports and other related documentation. In addition, they prepare statewide summary reports and serve as a contact for regulatory agencies. Finally, the office of maintenance ensures the SMAs are adaptively managed and works with the central geo–environmental section to facilitate annual reviews of the SMA program. If a site is not designated an SMA, the region environmental staff coordinate with the appropriate resource agencies and prepare the required documentation and coordinate with the district manager for any required mitigation. The central geo–environmental section provides funding to regions for monitoring SMAs, and for monitoring resources not associated with SMAs but that have regulatory monitoring requirements.

Automating Environmental Data Collection for Maintenance of Environmental Assets

Practical and economic considerations and technological advances necessitate ongoing exploration of what portion of asset management can be accomplished through remote sensing and automated monitoring. Oregon's sensitive area program is an example of much that can be accomplished with remotely sensed information to identify areas for different maintenance treatments.

Now several DOTs are looking at adding monitoring instrumentation to permanent BMPs. DOTs have used instruments for a number of years to help monitor bridge conditions, and automatically spray anti-icing compounds under specific weather conditions. In the Charlotte area, North Carolina DOT tested a system of water sensors combined with statewide weather information systems to time sampling with runoff from storm events. In Colorado, DOT used an automated system to monitor water quality during storm events and periods of snowmelt runoff. Monitoring stations at culverts measured the water quality of highway runoff including the effects of winter maintenance activities such as the application of sand and deicers that contribute pollutants to adjacent streams. The system also measured water quality changes in relation to sediment control measures implemented along the highway. Colorado DOT used this information to design unique sediment traps in specific locations that were easy to maintain using existing equipment.

DOTs have also used cameras at wildlife crossings to monitor use and effectiveness. Typically, monitoring data is collected by a university or wildlife organization and is not used to identify the need for maintenance of the crossing. Where electronic sensors are installed, they can convey data back to a uniform database that can be used between agencies who share management responsibilities.

Under these circumstances, sensors can result in a cost savings to the DOT because they provide information without requiring field visits in most cases, and data can be reviewed and analyzed to support decision making on needed action in maintenance.

Random Condition Assessment

When remote sensing, statewide inventories or annual inspections cannot be performed, random condition assessments (RCAs), as performed for some assets in Virginia and North Carolina, provide an option. Analysis of the data collected is linked to repair–cost strategies that will then be converted into network-level information required to determine an unconstrained statewide needs-based budget. Specific needs, as determined by the collection activities, can then be categorized into repair strategies. Each strategy requires a dollar investment to return a distressed asset to the specific service level or to maintain the asset at a current acceptable service level. The program is not intended to define a pass–fail condition for each asset. Instead, the software program determines a set of values expressed as a percentage or a number, for the asset being evaluated. This allows threshold values to be built into the business models for each asset (in much the same way as pavements are evaluated) that can then be used to calculate repair or replacement costs for specific asset types and conditions. In Virginia, this modeling allows DOT to determine the level of activity and cost that will likely be needed to return an asset to a serviceable condition or to optimize its life-cycle. In terms of asset modeling, this approach means categorizing assets by the opportune time to invest or less costly to repair or more costly to repair (Virginia DOT's prevent, repair–restore, or replace options) (*15*). Nevertheless, Virginia DOT includes only a very limited selection of environmental assets in their RCA:

- Cross pipes (no part of a bridge or culvert with a cross-sectional area equal to or greater than 36 ft^2 is to be included): exclude 6-ft^2 box culverts unless they have a structure number;
- Unpaved ditches–swales; and
- Unpaved shoulders.

Washington State DOT has developed a maintenance accountability process (MAP) tool and field manual to measure and communicate the outcomes of maintenance activities and to link strategic planning, budget, and maintenance service delivery. Twice a year, field inspections are made on randomly selected sections of highway. The results are measured, recorded, and compared to the MAP criteria to determine the level of service delivered. Results are summarized annually, with A (blue) through F (red, none) grades for drainage maintenance and slope repair and roadside vegetation management, as shown for 1 year, in Figure 1.

CONCLUSION

We found that few DOTs have begun to develop a statewide system for asset management of environmental mitigation features. However, several states are beginning to use environmental commitment tracking systems beyond the construction phase to monitor and maintain mitigation features. The most progress has been made in systems for vegetation management and culvert management as maintenance of these features is closely tied to routine maintenance of the major transportation infrastructure. In most states, however, monitoring and maintenance of most other mitigation features ends when the environmental permit is closed. When there is no permit, maintenance ends upon completion of construction. Funding and staffing constraints have impeded the ability of most DOTs to make substantive progress in developing adequate inventory data, condition assessment, and integrated management systems. DOTs are evolving a wide variety of mechanisms to help reduce the cost of maintaining environmental assets through

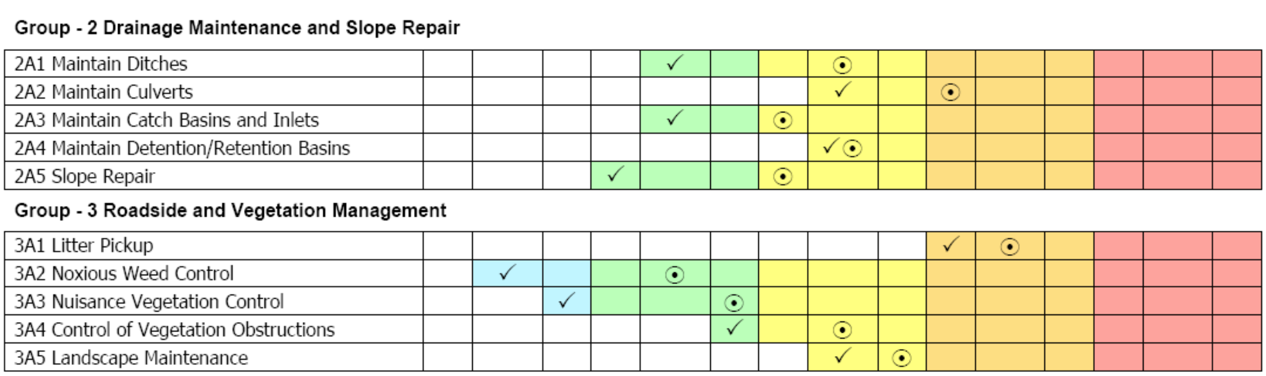

FIGURE 1 MAP result summary.

design, value engineering, or transferring ownership to a conservation agency for long-term maintenance.

A few states have made notable progress in moving toward a comprehensive system for long-term asset management. District of Columbia DOT has distinctive plans to track performance of environmental commitments in maintenance and corrective action. The specifics of staffing and when and how such monitoring will occur are yet to be determined.

Maintenance management and related systems are increasingly addressing and incorporating environmental components. For example, Pennsylvania DOT has linked maintenance equipment to a web-based GIS application that provides a centralized database for the maintenance and operations of the roadside IVM program. Other systems such as Washington State DOT's annual maintenance accountability process capture some environmental features maintained by DOTs, including some that are proactive rather than regulatory. Extending systems to track regulated environmental mitigation features is the current challenge for many DOT maintenance operations.

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ENVIRONMENTAL ASSETS, VEGETATION INVENTORY, AND MAINTENANCE ISSUES IN DESIGN AND CONSTRUCTION

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In 2008, a review of current Midsouth Department of Transportation (DOT) technologies, including cell phones with Global Positioning System (GPS) or camera capabilities, GPS units, and geographic information system (GIS) technology, was conducted to determine potential needs and compatibilities with newer software, databases, and other technologies available. A review of literature was also conducted to determine what technologies were most applicable for DOT. An investigation of Weed Information Management System developed by The Nature Conservancy, North American Weed Management Association data fields, and the Invasive Plant Atlas of the MidSouth database was conducted to determine how each is applicable in achieving DOT system goals. Various technologies, including GPS equipment and software, were acquired for field testing to determine compatibility with DOT applications. The development of a user training manual was initiated, based upon information gathered during the study, to assist DOT personnel with utilization of field equipment, form completion, download methodology, software, and database applications.

Solving Maintenance Issues in Design and Construction

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The maintenance and operation of a highway system includes many different tasks on major assets such as pavements and bridges as well as many other corollary tasks on the roadside and other appurtenances. Generally the better the materials that are used in the original construction, the longer lasting they are and the lower the life-cycle maintenance costs will be. This paper will explore the many relationships between the design of a highway facility, the selection of the materials that go into the facility and the quality of construction on the life-cycle cost of the facility.

The cost of maintenance is directly proportional to the design, the quality of materials, and the quality of construction methods. This paper will discuss many of the issues caused by poor materials or construction and will recommend designs, materials, or construction techniques to lower the overall life-cycle cost of maintenance. Some are more serious than others; some are design issues while others are material selection or specification problems. Many other problems are built into roads by poor quality construction. They are categorized in some broad categories.

CROSS-SECTION DESIGNS

Ditch Depth

Some roads designed where the water is carried on the shoulder, with the back slope in cut sections beginning at the edge of the pavement. One of the most important aspects of pavement maintenance is to get the water off and away from the pavement. Water that gets into pavement foundations whether from the bottom, top, or sides causes problems. Ensure enough right of way (ROW) is available to provide an adequate ditch where the water can run off without getting into the base (Figure 1).

FIGURE 1 Inadequate ditch forces water onto the pavement.

Side Slopes

Provide a minimum of a 3:1 back slope. Frequently designers steepen the back slope to fit widening on the existing ROW. This causes erosion, slides, hard to maintain slopes, or other problems. Retaining walls are more preferable than a 2:1 back slope. If a mower does get on a steep back slope, they end up tearing it up to mow it and they put themselves in danger of turning over.

Radiuses

Provide proper radiuses for truck turning (Figure 2). Turning vehicles will widen the pavement as necessary.

Pavement Widths

A two-lane road should be no narrower than 28 ft. Maintenance forces are constantly working on raveling edges, edge failures, or edge drop offs where traffic is running on the edge of the pavement or off the pavement, especially on winding roads. A narrow shoulder, even as little as 2 ft will pay great dividends when it comes to maintenance costs, pavement preservation, and safety (Figure 3).

Shoulders

Don't thin down the shoulder section to save money. Some day that shoulder will be used as a travel lane temporarily while the main lane is being worked on. There is nothing worse than working on the main lane and carrying traffic on the shoulder while traffic tears up the shoulder, requiring maintenance to rebuild the shoulder right after they get through rebuilding the main lanes.

FIGURE 2 Truck traffic has created a severe rut along pavement, even behind curb.

FIGURE 3 Narrow pavement creates edge problems.

Crossovers

If at all possible, eliminate cross over culverts by moving crossovers to the top of a vertical curve or by utilizing them as ditch blocks. Also from a safety perspective line them up with existing driveways when possible.

TRAFFIC OPERATIONS

Signs

Eliminate them if possible. Signs are continual maintenance—to keep the posts plumb, to make sure they are still reflective at night, to make sure they are not blocking the sight distance at intersections or the view of other signs, etc. If signs are optional, leave them out unless there is a compelling safety issue. Texas Department of Transportation's current design philosophy is to provide a substantial foundation so it can be reused in case of a hit. This results in a lower life-cycle cost.

Move them away from the edge of the pavement. Move signs as far away from the pavement as possible, ensuring good sign visibility. At T intersections, move the signs across from the intersecting road back to the ROW line and move them out of line with the oncoming traffic from the intersecting roadway. If someone does run through the intersection, they won't hit the signs.

Crossovers on four-lane divided highways are signed anywhere from having a single delineator on each side, to having a complete complement of signs—from "crossover ahead", "crossover", "one way" signs, "do not enter" signs, and "stop" or "yield" signs. The two extremes range from two delineators to 14 signs (Figure 4). From the maintenance perspective fewer is better. From the traveling public's perspective, a few delineators or raised pavement markers along the turn-lane stripe will delineate the crossover. All the "crossover", "one way", "do not enter," and "stop" signs are unnecessary.

Utilize a mow strip. A sign that is out on the ROW for 10 years will have to either be treated with herbicide or trimmed around 30 to 50 times. By providing a small concrete pad around the sign, weeds will not grow up around it and mowers are less likely to hit the sign.

Utilize fiberglass sign posts for stop signs (Figure 5). Where a metal post will bend and be unusable, fiberglass sign posts will break when hit and they usually can be cut off and placed back into the foundation socket. This can be done by law enforcement or any highway agency employee that happens by a downed sign. They may be too short, but there will still be a stop sign up, that can be reinstalled to regulation height at a later date.

FIGURE 4 Crossover with many unnecessary signs.

FIGURE 5 Fiberglass sign post with universal mount.

Attenuators

Think of maintenance when selecting attenuators (Figure 6). All of them are crash tested to ensure compliance with NCHRP 350 requirements; however, they are not all created equal when it comes to repair. Some have components that will have to be replaced when an impact occurs. Some are completely sacrificial and a new attenuator has to be installed. The ones desired by maintenance engineers can be repaired by pulling them back into place or quickly replacing severely damaged components. They require shorter periods of time for the maintenance crews working in an unsafe location and improved safety for the traveling public.

FIGURE 6 Easy-to-maintain attenuator.

Luminaries

Lighting applications are continual maintenance headaches, from the electrical consumption and from the maintenance perspective. Typical roadside lighting involves high voltage (frequently 480 V) and many components such as fuses, electromagnetic contactors, photo cells, switches, fixtures, conduit, and different types of bulbs. Not only are they very technical, requiring highly skilled workers, but they are dangerous to work on and difficult to keep in good condition. To that end, as few lights as possible should be installed. Those that are installed should be as simple as possible and include lower-voltage lighting if possible. Low-voltage, long-lasting LED lighting is being developed that will save money both on electricity costs, but also in bulb replacement, as they will have a life expectancy approximately four times that of gas-filled bulbs. Illumination for overhead signing can be eliminated by the use of prismatic sheeting.

Delineation

Delineation is a critical part of the highway roadside, but is also difficult to maintain. Galvanized metal delineator posts oxidize and get dirty with time making them very difficult to see, even in the daytime (Figure 7*a*). In addition, they will not take any type of hit without bending. Errant vehicles, vehicles trying to park on the roadside, or mowers frequently hit delineators. Even a tire passing close to the delineator in loose or wet soil will cause it to lean. Some of the flexible delineators on the market are effective and utilize a highly visible white color (Figure 7*b*). They can usually take multiple hits without needing to be replaced. However, they also are not all created equal. The fiberglass delineators will stay straight and can be driven into the ground, but they fade or get dirty through time, may blow in the wind, and become brittle. Some of the plastic ones are too flexible and may follow the sun as the plastic expands or contracts in the summer sun.

a

b

FIGURE 7 (*a*) Metal delineator blends in and is frequently hit, but (*b*) white delineator with solid base stands out and is easily replaced.

Some of the best ones have a substantial base that gets installed in concrete and although more expensive initially, remain straight, and, if damaged by a direct hit, are easily repaired by removing the old delineator and installation of the new one in the same base.

ROADSIDE ISSUES

Islands

Islands are typically used to separate traffic or provide positive directional barriers. While they are necessary in many cases, they can cause safety problems and maintenance expenses. In T intersections stop signs are frequently mounted in the center of the road in the island. Many times the islands are safety problems, creating a difficult-to-see obstacle at night. In theses situations, islands should be removed whenever possible. The utilization of raised pavement markers mounted directly on the pavement are more visible than an island and are much more effective in identifying an intersection at night. In addition, the stop sign should be moved to the side of the road if at all possible to reduce the number of impacts to the sign.

Designers also frequently use islands for landscaping. Islands are difficult to access even with medium traffic volumes and create unsafe locations for maintenance workers (Figure 8). In addition, landscaping frequently requires irrigation, causing problems with leaking irrigation systems, water blowing onto the pavement, frequent water standing on the pavement causing failures, etc. If islands are necessary, use concrete paving to eliminate continual maintenance. It can be colored or stamped to improve the aesthetics. A paved island also provides for litter to blow off, reducing the need for litter pickup. Pavers are not a desirable option because they frequently get weeds and vegetation growing up in them.

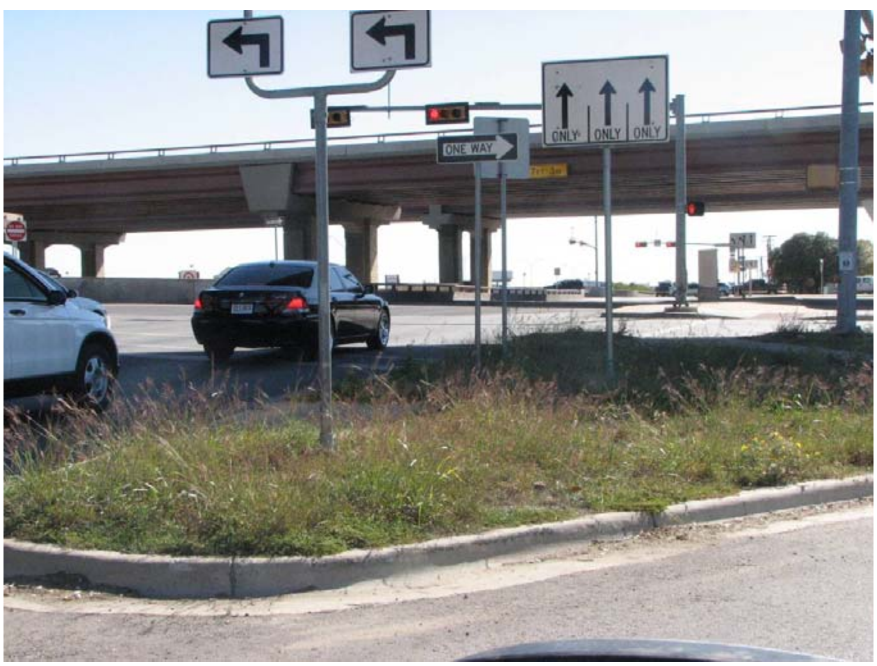

FIGURE 8 Island that is hard to access.

Guardrail

Guardrails should be considered a last resort when attempting to provide a safe roadside. Designers should treat guardrails as just another object on the roadside for the traveling public to impact. If at all possible, the hazard should be treated, moved, or eliminated instead of placing a guardrail. For example, guardrail is frequently installed to keep a vehicle from impacting a culvert end, column, or other object or to keep them from driving off a drop-off or steep slope (Figure 9). A simple question should be asked before designing guardrail: can the design at the location be improved instead of installing guardrail? For example, can a sloped end be installed on the pipe instead of a guardrail? Can the slope be flattened? Can the luminary be moved? Can the camera pole be moved? Can a mountable drop inlet be installed? Frequently a traffic cabinet, camera pole, or other appurtenance is installed on the ROW and a guardrail installed to keep traffic from hitting it when it could have been moved a few hundred feet behind an existing barrier or rail. Guardrails can also cause access problems where mowers or other maintenance equipment cannot access areas.

Cable Barrier

Many states are installing miles and miles of cable barrier in medians (Figure 10). While it is one of the most cost-effective methods of substantially reducing cross-over head-on collisions and by

FIGURE 9 Guardrail (350 ft) installed to protect cabinet; move cabinet instead.

FIGURE 10 Cable barrier adjacent to travel lane receives many nuisance hits.

itself is relatively easy to maintain, it can cause substantial maintenance problems. Designs should take into consideration access issues and mowing. Installations should be made as far away from the pavement edge to reduce nuisance hits. Adequate distance should be left between the barrier and travel lanes to ensure easy mowing. Mow strips (concrete pads a few feet wide) should be installed to reduce the need for hand trimming or herbicide. A few problems that were noticed include: cable that was placed at the edge of the pavement picked up frequent (almost daily) nuisance hits and cable placed about 4 ft off the pavement required mowing contractors to include a 4-ft mower in the equipment fleet that usually included only 15-ft bat wing mowers (increased mowing costs). Cable that terminated about 4 ft behind guardrail prohibited access between the cable and the rail (Figure 11). Also miles of cable that was installed with no mow strip required miles and hours of hand trimming.

Mow Strips

Hand trimming around signs, under guardrails, under cable barriers, and along walls creates a large workload for highway maintenance workers that can be eliminated with the installation of concrete mow strips. These are small concrete pads that are poured under and around roadside features. These mow strips substantially reduce or eliminate the need for years of hand trimming (Figures 12 and 13).

FIGURE 11 Cable barrier terminates behind guardrail, creating inaccessible area.

FIGURE 12 Good mow strip along retaining wall eliminates hand trimming.

FIGURE 13 Good mow strips under rail and around luminary.

Mail Boxes

Mailboxes are also an item on highway ROWs that cause many maintenance issues. A few states have established crash-tested standards and only allow those standards on the highway ROW. By establishing standards, unsafe mailboxes can be eliminated and the locations of mailboxes can be controlled. Where wide shoulders are available (>8 ft), mailboxes may be placed adjacent to the pavement where they can be serviced by vehicles on the shoulder. Where there are no shoulders or narrow shoulders, paved mailbox turnouts should be provided. This not only gets the postal carrier and mailbox owner off the travel lane providing for a much safer situation, but also eliminates pavement drop-offs, raveling, and frequently holes or depressions along the roadside that hold water and allow for water to seep into the base (Figures 14 and 15).

FIGURE 14 Mailbox turnout with rap installed to eliminate water standing area.

FIGURE 15 Water standing where no turnout is installed.

Driveways

Typically states do not maintain private driveways on the state ROW. However, frequently pot holes form in gravel or paved private drives. These holes are typically adjacent to the pavement edge allowing for standing water to penetrate the roadway foundation (Figure 16). Failures that begin in a driveway frequently propagate into the travel lane. Provide for repairs and preventive maintenance treatments for 2 to 3 ft of the driveway adjacent to the shoulder or travel lane to ensure failures do not propagate into the travel lanes.

FIGURE 16 Unmaintained driveway provides location for water to get into roadway base.

BRIDGE DESIGN

Many bridge designs have inherent maintenance problems built in to them. There are some components that provide for lower maintenance.

Railing

Debris

Debris builds up along solid railing causing constant attention to remove tire tread, ice rock, and various other items that fall or blow out of vehicles. Providing open railing allows for debris to blow off the roadway and rain to keep bridges clean. The debris also holds the water and ice-melting chemicals on the bridge causing deterioration of the steel and concrete.

Design

Bridge railing should be designed where it is easily maintained. Concrete railing is preferable to steel because it will take substantial hits before it is damaged. Also steel rail needs to be repainted.

Painted Concrete

Painted beams, caps, columns, and railing are maintenance headaches. Frequently the paint peels, it gets graffiti, it gets hit, or it fades over time. Paint colors are very difficult to match and even if some of the original paint is retained for touch up, it never matches because the original fades. Although paint is installed for aesthetic purposes, it frequently causes aesthetic problems in time.

CONCLUSION

Many items that can have a major positive affect on maintenance are easily taken care of by proper design, material selection, and construction practices. Many times these changes can be done at very low or no cost. Even though statutes frequently require low bid for the selection of materials and projects, specifications and practices can be utilized that will provide for the lowest life-cycle cost to the highway agency.

APPENDIX

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