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Maintenance Management 2012

Presentations from the 2012 AASHTO–TRB Maintenance Management Conference

Seattle, Washington
July 15–19, 2012

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Preface

This publication contains papers presented at the 2012 AASHTO–TRB Maintenance Management Conference held in Seattle, Washington, July 15–19, 2012. The objective of this series of conferences is to provide a forum every three to four years for the exchange of new ideas and developments in the maintenance and operations management of transportation facilities. The conference was hosted by the Washington State Department of Transportation and jointly sponsored by the Transportation Research Board, the American Association of State Highway and Transportation Officials, and the Federal Highway Administration 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 maintenance, 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 the Transportation Research Board, 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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ISSUES IN PAVEMENT PRESERVATION AND MAINTENANCE

Using Automated Pavement Condition Measurements to Indicate Appropriate Pavement Preservation and Maintenance Options

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International roughness index (IRI) in each wheelpath, the difference in IRI between each wheelpath, crack counts, and texture data were used to evaluate the pavement condition of federal aid roadways in three Alabama counties. Analyses of these measurements showed that the differences in IRI between the right and left wheelpaths can be used to indicate the need for load-carrying support improvements to provide longer performance. Pavements in good condition and with adequate support had IRI values of less than 175 in./mi, differences in IRI between wheelpaths of less than 30 in./mi, and fewer than five cracks per mile with enough deterioration to influence ride quality. Preservation treatments such as fog seals, rejuvenating seals, sand seals, and crack sealing would help maintain the current good condition of the roadways. Roadways with IRI values in the left wheelpath of less than 175 in./mi, but with significantly higher values in the right wheelpath (differences greater than 30 in./mi), were associated with visual observations of edge distresses, depressions, bumps, and patching. In these cases, there is inadequate support for the traffic loads. Any maintenance or rehabilitation efforts should include improving the base properties (e.g., full-depth reclamation) or drainage. Pavements with both high IRI values and high crack counts are in need of rehabilitation. Alternatively, if the funding is not available for reconstruction, thin surface treatments such as chip or cape seals, and chip over fabric, would at least minimize further deterioration.

Pavement condition data historically has been used in pavement management systems (PMS) to identify roads in need of maintenance or rehabilitation. In state agency PMS programs, the pavement condition is rigorously collected using either time-consuming walking condition surveys or high-quality and expensive technology. PMS for local and regional engineers commonly consists of simple windshield surveys that are team assessments of ride quality and general ratings of distress extent and severity that are visible while driving. This type of survey yields subjective rather than quantifiable estimates of pavement condition. Automated technologies provide quantitative measurements for pavement condition surveys but are cost prohibitive for use by county agencies. The use of some of the more economical electronic technologies can provide quantifiable measurements of the pavement condition for local and regional engineers.

BACKGROUND

Automated information obtained using combinations of lasers and accelerometers, without the use of expensive digital imaging, has the potential to provide basic information on the roadway condition. Chatti and Lee (*1*) showed that there is a reasonable expectation of an exponential

relationship between the ride quality and the age of a pavement. These researchers recommended the use of ride quality statistics as a simple trigger for pavement maintenance activities. Richter (*2*) reports that not only is there a reasonable expectation of an exponential relationship, but the ride quality decreases faster for pavements with subgrade and base materials with high fines and high plasticity. Fernando and Bertrand (*3*) document that the profile used to calculate ride quality can also be used to identify localized distresses such as bumps in the surface. Brock (*4*) indicates that the percent of cracking is significantly reduced when a smoother initial ride quality is achieved. This previous research suggests simple automated pavement condition information such as ride quality and crack counts in each wheelpath could be useful in pavement management programs. This research evaluated alternative uses for simple automated data collection to indicate loss of smoothness as a result of the loss of base–subgrade support, raveling, and moderate to severe thermal and age-related cracking in the outer wheelpath.

OBJECTIVES AND SCOPE

Objectives

The objectives of this research were to (*a*) characterize the international roughness index (IRI), cracking, and texture trends for each of three Alabama counties, and (*b*) assess implications of measurements for optimizing prevention and maintenance treatment options.

Scope

Three counties in Alabama were used for this study. The county engineer for each county provided their most recent Maintenance Inspection Reports were provided by the county engineers for all of the state and federal fund roads with lengths of more than one mile and consistent speed limits of 45 mph. These criteria provided a list of about 300 miles of paved roads in each county that were evaluated with an inertial profiler capable of measuring the IRI in both wheelpaths, texture in the right wheelpath, and moderate to severe transverse cracks in each wheelpath. The data collected includes the IRI in wheelpaths (laser–accelerometer sensor system), cracking, and texture with a high frequency laser in the right wheelpath. The occurrence of sharp discontinuities in the longitudinal profiles is logged as "faults." In the case of flexible pavement, the automated "fault count" indicates moderate or high severity transverse or block cracks which result in a discernable bump in the ride quality.

PROJECT DESCRIPTIONS

Most of the roads surveyed were two-lane facilities with varying lanes widths and no shoulders. The general climatic information (Table 1) was assembled from LTPPBind V3.0 and the National Climatic Data Center (*5*–*6*). Counties 1 and 3 have similar high and low temperatures and numbers of freeze-free days. County 2 is the southern-most county and has a slightly warmer low temperature but noticeably higher population, traffic levels, number of freeze-free days, and annual precipitation.

Information obtained from conversations with long time agency staff were used to estimate the general pavement structure typically used over the years in each county. In general

- County 1: Roadways were historically constructed using a 4- to 6-in. base of agricultural land soils followed by 1 to 3 in. of surface treatment, or thin hot-mix asphalt (HMA) treatment. More recent maintenance operations use a thin HMA overlay over the existing surface.
- County 2: Most roadways were constructed using a sand–clay base followed by thin surface treatments or 1 to 3 in. of HMA surface in the more urban areas.
- County 3: Most roadways are in either rural or recreational areas with roadway structure limited to prepared subgrade followed by thin, coarse surface treatments.

DATA COLLECTION

A Roadware ARAN van was used to collect IRI, rutting, transverse cracking, and texture data. IRI values were calculated for every 53 ft of linear roadway. This interval is 1/10th of the standard 528 ft (0.1 mi); the shorter interval was selected in order to highlight anomalies that can influence a driver's perception of ride quality (e.g., bumps and dips due to patching). The texture, expressed as the mean profile depth (MPD), was collected in only the right wheelpath (*7*).

The ARAN Roadware unit registers a fault when there is a difference between the midpoint heights of two consecutive 2-ft-long profile sections. For this study, a criterion of a difference of greater than 0.11 in. was used. Any crack that extended across a single wheelpath

TABLE 1 Summary of County Statistics

Information	County 1	County 2	County 3
General County Information			
General location in state	Eastern	Southern	Central Eastern
Square miles	609	1,644	701
Population (2002)	115,000	300,000	41,475
Paved roads (miles)	611	832	520
Unpaved roads (miles)	225	543	420
County Climate Conditions			
Average low temperature (°C)	–12.1	–7.6	–13
Average high temperature (°C)	35.1	35.3	34.7
Average drop in temperature (°C)	28.6	25.1	29.3
Precipitation	53	66	52
Freeze-free days	219	273	199
Roadway Information			
Traffic range (ADT)	430 to 8,000	600 to 15,000	100 to 8,000
Typical lane width (feet)	8 to 9	9 to 11	8 to 9
Number of roads surveyed	30	33	103
Average length of roadway (miles)	4.5	5.8	2.5
Year data collected	2002	2003	2004

NOTE: ADT = average daily traffic.

had the potential for being identified by the laser in that wheelpath. Therefore, while cracks are referred to in this paper as being transverse, they can also be part of a block crack that crosses only one wheelpath. Since the software logs cracks in either wheelpath, a spreadsheet was used to calculate the distance between two sequential cracks, regardless of wheelpath. The premise was that if it was a transverse crack, it would eventually extend across the full lane width. If the crack was part of a block crack, this analysis approach will still provide an estimate of the spacing in the block pattern.

RESULTS AND DISCUSSION

International Roughness Index

Distresses that are expected to influence ride quality include

- Transverse cracks that have either deteriorated or allowed moisture intrusion to produce a localized depression;
- Alligator cracks that have deteriorated into either potholes or patched potholes; and
- Edge distresses that have either been patched or are manifested as corrugations along the outer wheelpath.

These distresses increase with time, so IRI is expected to increase with time. Figure 1 shows this general trend is followed when the IRI measurements from all three counties are combined. The IRI in the right wheelpath which is the closest to the unsupported shoulder is routinely rougher than the inside left wheelpath. The left IRI is about 60% that of the right wheelpath (slope of regression line). The difference in IRI between the wheelpaths also increases with increasing roughness at a rate of about 40% of the right wheelpath IRI increases.

The range of values for each measurement was used to determine the frequency of ride quality characteristics (Table 2 and Figure 2). About 90% of the roadways in County 2 have right wheelpath IRI of less than 175 in./mi indicating good ride quality throughout the region. Both Counties 1 and 3 had significantly more roughness in their roadway network. Approximately 63% of the roadways in County 1 were below 175 in./mi while only 40% of County 3 roadways were below this value.

The distribution of differences shows several key points to differences in roadway conditions and hence different selections of optimum pavement preservation, maintenance, and rehabilitation treatments (Table 2 and Figure 3). Fifty percent of County 2 IRI differences were less than 15 in./mi which indicates the roadways are performing uniformly across the lane with little rough deformation in the outer wheelpath. Both Counties 1 and 3 have only about 20% of roadways with this level of uniformity. Since the load carrying ability in County 2 is providing consistently smooth and uniform ride, pavement preservation rather than maintenance treatments (e.g., fog seals, rejuvenating seals) should be emphasized to sustain this level of condition. However, County 1 roadways have fairly smooth roadways in the inside wheelpath but are significantly higher in the right wheelpath. The significantly rougher ride in the right wheelpath corresponds with increased patching and edge failures noted in the visual inspection notes Therefore, the loss of base and subgrade support should be considered important in any preservation or maintenance treatments. The IRI values for County 3 roadways have similar

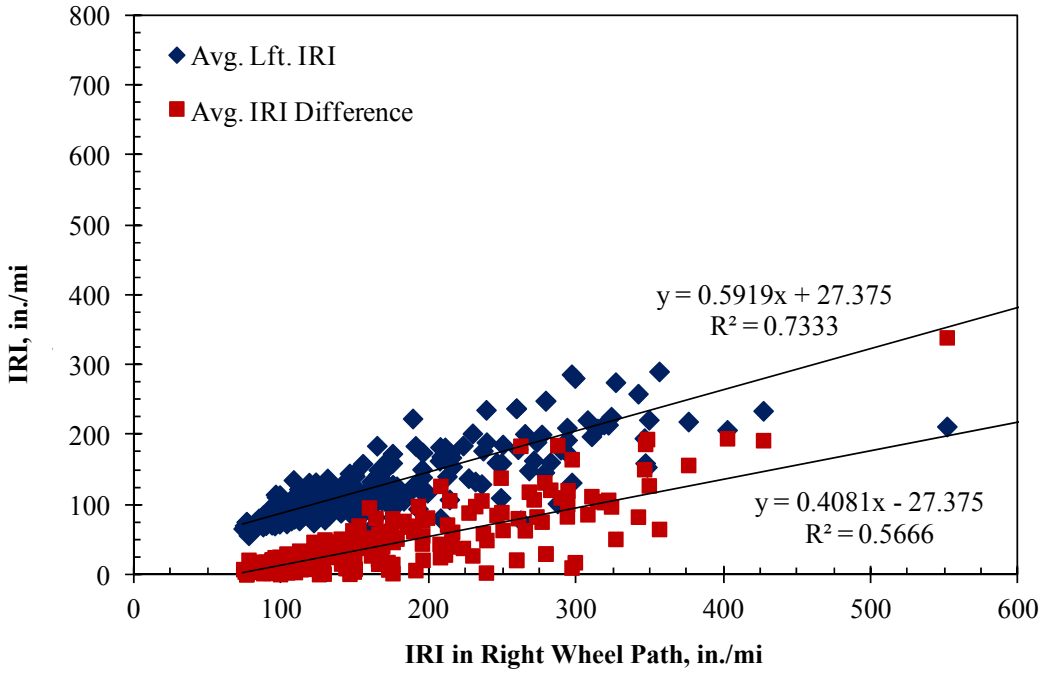

FIGURE 1 Relationships between IRI measurements for data from all three counties.

TABLE 2 Summary of Percent of Roadway Conditions for Each County

Measurement	Frequency (%)	County 1	County 2	County 3
IRI in right wheelpath	90	248.62	174.35	341.79
	75	195.41	144.13	281.26
	50	152.05	118.47	195.64
	25	125.33	98.47	131.75
	10	101.82	87.23	111.90
IRI difference	90	106.12	46.90	121.35
	75	70.15	25.67	86.37
	50	40.38	15.30	45.64
	25	21.13	7.50	21.39
	10	2.99	–0.57	10.16
Cracks	90	11.90	2.23	633.73
	75	3.40	1.23	455.66
	50	1.67	0.34	100.52
	25	0.52	0.12	24.27
	10	0.29	0.05	10.40
Texture	90	2.27	1.68	2.53
	75	1.39	1.28	1.67
	50	0.90	0.90	0.79
	25	0.62	0.46	0.55
	10	0.47	0.30	0.44

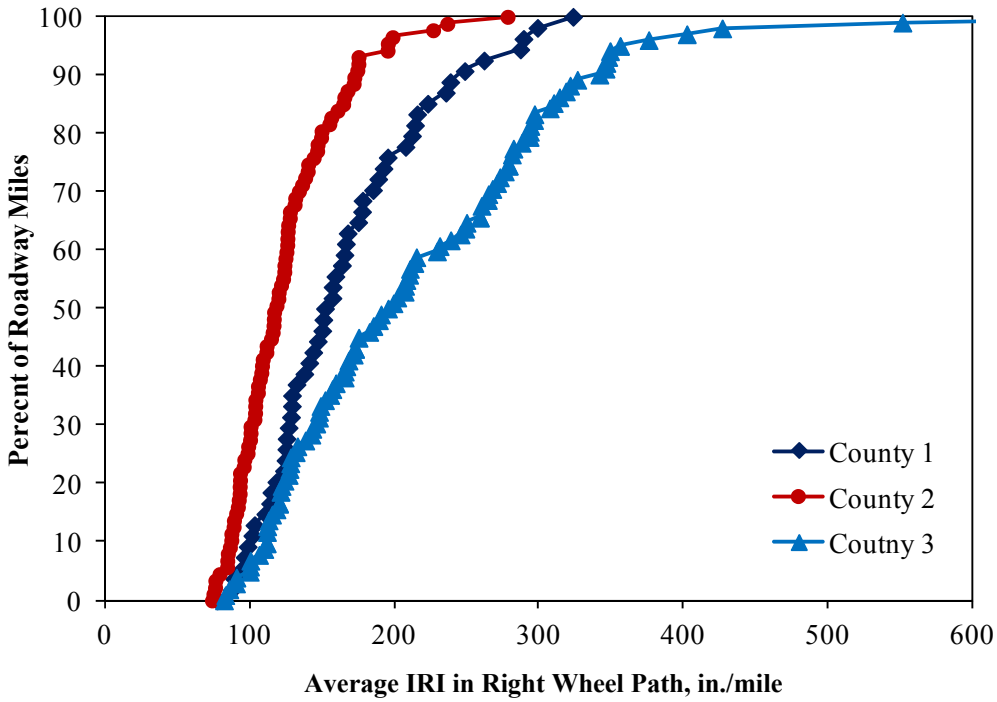

FIGURE 2 Percent of individual county IRI right wheelpath measurements.

differences in ride between wheelpaths (Figure 3) but are significantly higher than County 1 (Figure 2). The majority of these roadways are located in the most rural areas surveyed. The County 3 roadways also appeared to be substantially older than any roadways in the other two counties.

Crack Counts

Transverse cracks occur as the result of thermal changes generating stresses in the pavement that exceed the HMA ability to dissipate stresses; meaning that the HMA layer is not sufficiently ductile to resist cracking. The daily thermal differences in the areas surveyed for this study are not large (i.e., ΔT of around 20°F to 30°F). Therefore, the occurrence of transverse cracks is considered to be the combined effect of the aging of the asphalt binder (embrittlement) and environmental factors (e.g., ultraviolet light, precipitation). Both thermal and block cracking will be included in this measurement.

The distribution of roadways in each county with measurable cracking in one or both wheelpaths is shown in Table 2 and Figure 4. Figure 4 suggests that the increased roughness for County 3 is most likely a function of both the transverse and block cracking in the roadways. Visual observations indicated the majority of the cracking is a function of advanced age (e.g., block cracking). While the IRI difference between the wheelpaths in County 3 was similar to that for County 1, the cracking is likely the major contributor to roughness. This also suggests the loss of support in the right wheelpath in County 3 is likely a function of moisture intrusion into the base and subgrade through the cracks over time, which seals the surface such as chip or slurry seal. Ideally, these roadways are in need of reconstruction. Full-depth reclamation followed by a chip seal would be one example of an acceptable rehabilitation treatment. Further investigation shows a fair correlation between cracking and roughness for County 3 but little

apparent correlation for either County 1 or 2 (Figure 5). A closer view of cracking and IRI relationships at the lower crack counts shows the crack counts in Counties 1 are mostly below five cracks per mile. In County 3, about 60% of the roadways have less than five cracks per mile. County 3 has shows increasing crack counts which are fairly well correlated with changes in IRI.

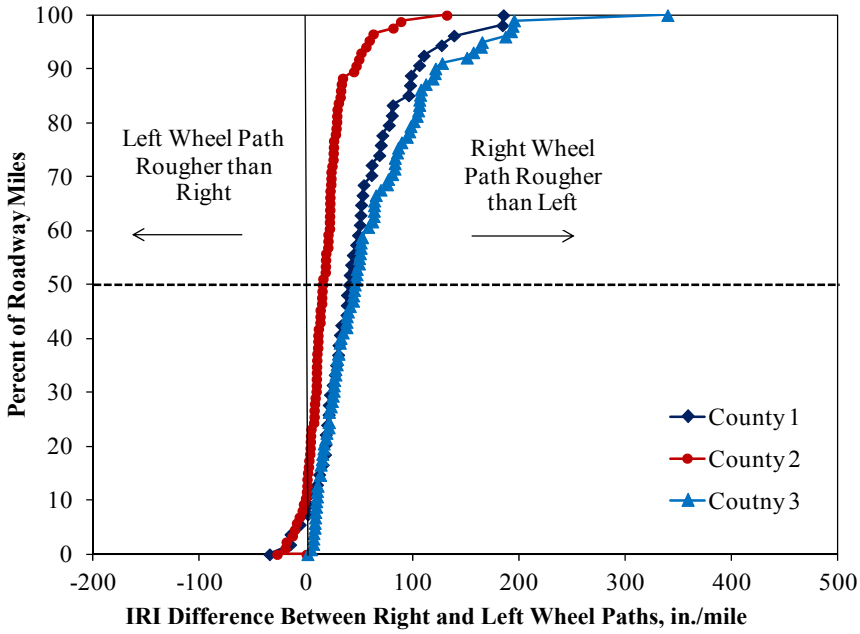

FIGURE 3 Individual county differences in IRI between wheelpaths.

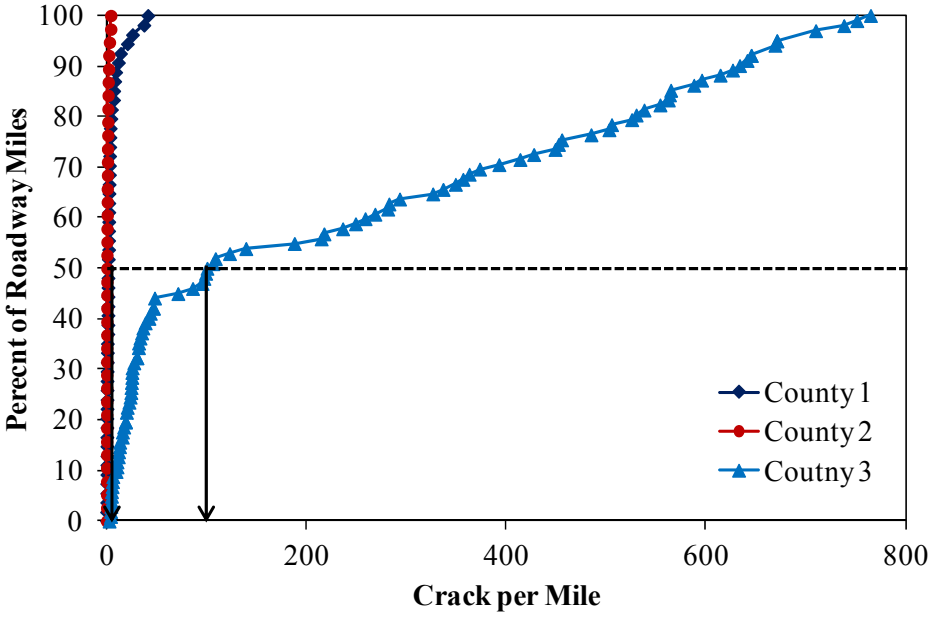

FIGURE 4 Individual county cracking measured in the wheelpaths.

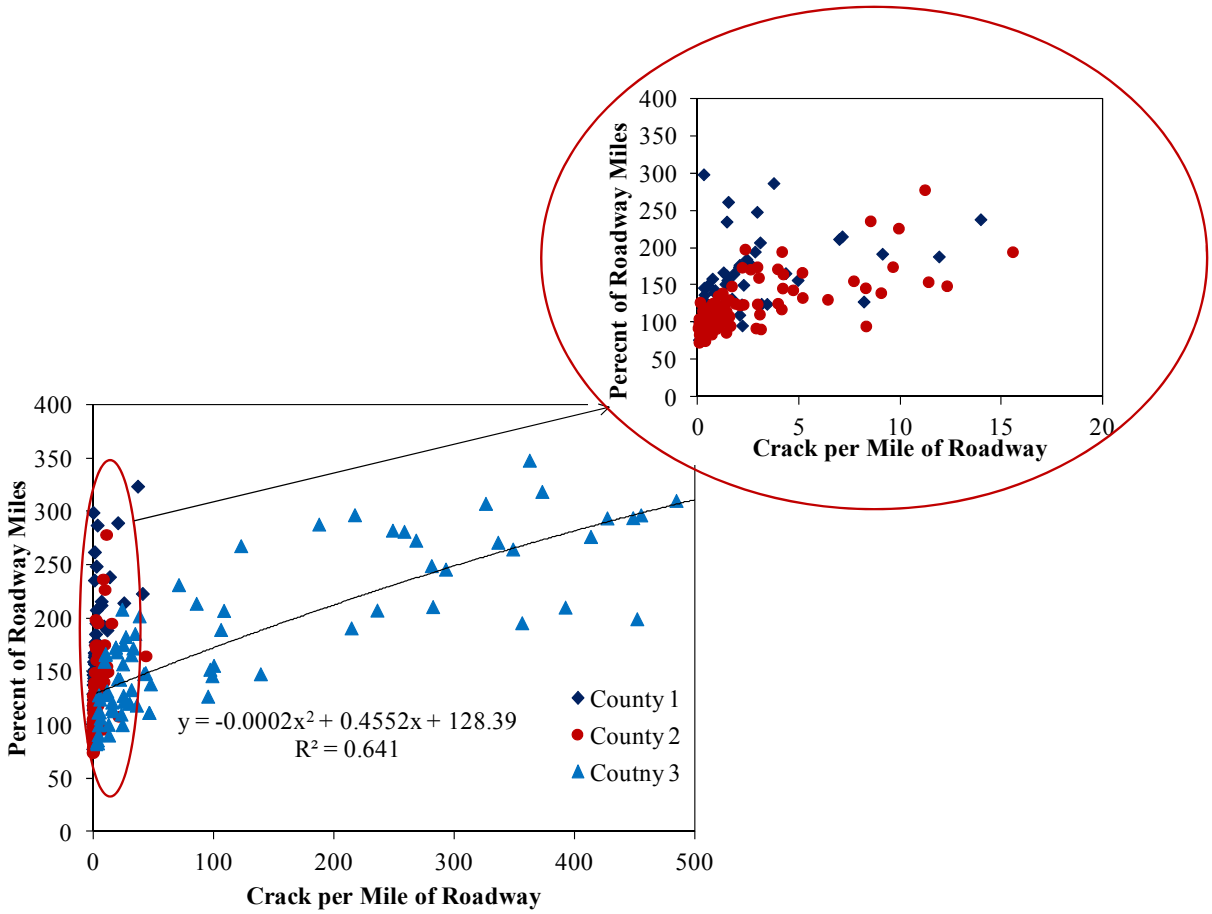

FIGURE 5 Influence of crack counts on ride quality for the individual counties.

Texture Measurements

Increases in the original texture are expected to reflect raveling due to weathering and traffic abrasion, deterioration of transverse cracks, alligator cracking, and patching. All of these distresses occur over time, and in the case of alligator cracking, a function of both traffic and the increased stiffness (brittleness) of the thin HMA layer with time.

Various other analyses were attempted to relate changes in texture to the extent of patching (visually rated with windshield survey during profiling) in the wheelpaths. However, no good relationship was found. This was attributed to the observation that there was no consistent patching mix gradation; some patches used a very fine mix while others used a very coarse mix. Also, some appeared to be over-asphalted while others appeared very dry. All of these factors will influence texture measurements.

About 50% of the textures for all three county roadways were below 0.9 mm of mean texture depth (Figure 6). The small group of County 1 roadways with textures greater than 1.5 mm represented a small number of roadways older than 40 years which were constructed using a very coarse surface treatment over subgrade. The courser textures for 50% of the County 3 roadways also indicate the prevalence of very old coarse surface treatments.

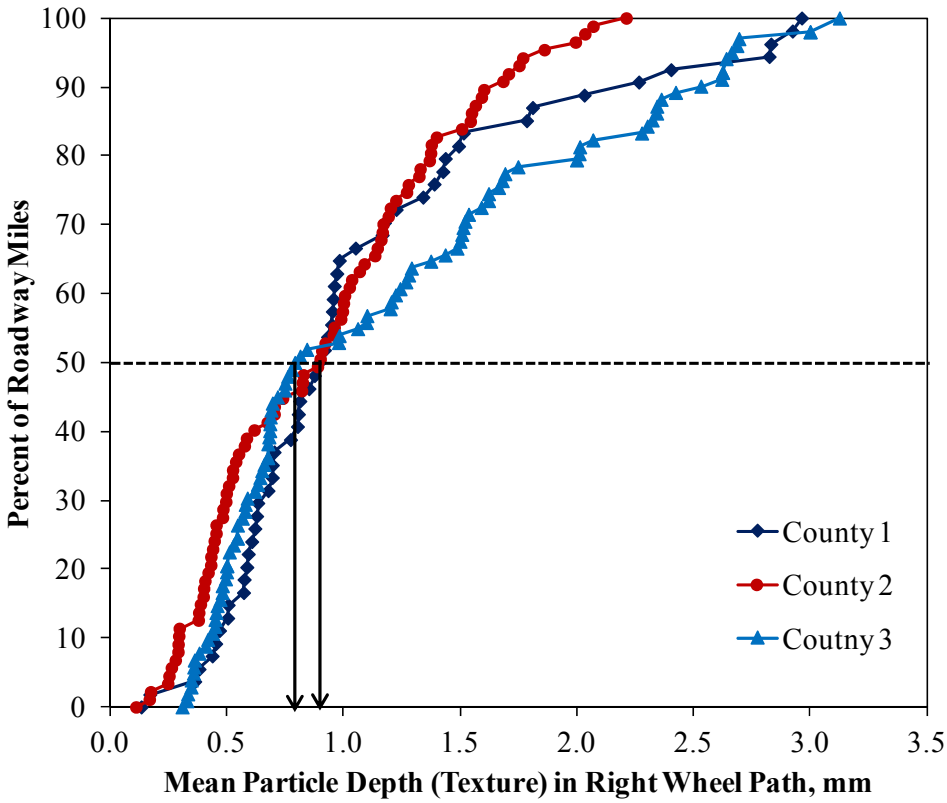

FIGURE 6 Individual measurements of roadway texture for each count.

CONCLUSIONS

IRI in each wheelpath, the difference in IRI between each wheelpath, crack counts, and texture data were used to evaluate the pavement condition of federal aid roadways in three Alabama counties. Characterization of county roadway condition using automated data collection:

1. Historical construction practices of using sand-clay base, a form of stabilized base using locally available materials, results in a roadway network with good ride quality, and little evidence of a loss of load carrying support in the right wheelpath. In this study, the IRI in the right wheelpaths were consistently below 175 in./mi with a difference in roughness between wheelpaths of less than 30 in./mi. Roadways with less support (agricultural till as base) produced roadways with significant differences in roughness between the wheelpaths. About 50% of all the county roadways surveyed had texture measurements below 0. 9 mm of mean texture depths. Textures higher than 1.5 mm were associated with old, coarse surface treatments that were over 40 years old.
2. Roadways with good IRI values in the left wheelpath (less than 175 in./mi) but significantly higher IRI values in the right wheel. Differences of more than 30 in./mi path were associated with the occurrence of edge distresses and patching in the outer wheelpath. Any

maintenance or rehabilitation treatments should address improving the base and subgrade support.

3. Roadways with little cracking, adequate support across the lane width, and good ride quality have IRI values less than about 175 in./mi, differences in IRI between wheelpaths of less than 30 in./mile, and moderate to severe crack counts per mile of about five or less.
4. Crack counts below 20 per mile may, or may not be correlated with changes in ride quality. However, when the crack count exceeds this limit, there is a fair correlation between roughness and ride quality.
5. When the differences in IRI between wheelpaths is greater than 30 in./mi, improvement of the subgrade and base course support should be considered in any maintenance or reconstruction treatment.

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ISSUES IN PAVEMENT PRESERVATION AND MAINTENANCE

Improvements in Asphalt Rubber Chip Seal Application with Warm-Mix Technology

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Asphalt rubber (AR) chip seals are normally more capable of resisting reflective cracking and more durable than conventional seal coat. However, the AR chip seal has very high production and construction placement temperatures. The temperature of mixing binder with crumb rubber modifiers ranges from 350°F to 425°F. The binder application temperatures are normally more than 350°F. The odor from tire rubber and emissions is also high. Adding warm-mix additives to the AR for the spray application can result in many advantages, including reduced odors, decreased emissions, and potential fuel savings. In 2010, three AR chip seal with warm-mix projects were placed in northern, central, and southern California, respectively. The binder placement temperatures were lowered about 45°F to 60°F, which significantly reduced emission, smoke, and odor. In California, the use of a warm-mix additive also eliminates the requirement of a special hood for conventional AR chip seal application required to meet U.S. Environmental Protection Agency emission regulations. The long-term performance of adding warm-mix additive to the AR chip seal application still needs to be evaluated. After 1 year of study, the initial results of using AR chip seal with warm-mix additives are promising. Several more AR chip seals with warm-mix additive projects were placed in California in 2011, and it is expected more will be placed again in 2012.

BACKGROUND

Asphalt rubber (AR) is produced by mixing crumb rubber modifier (CRM) from waste tire with asphalt binder at relative high temperatures. AR field blend is a wet process, normally requiring higher mixing temperature and placement temperature than other binder types. AR has been successfully used in the United States since 1960s. Various states have different standards in producing AR. Most states require the CRM percentage to be higher than 18% by weight of asphalt binder. California also requires certain percentage of high natural rubber and extender oil to enhance the performance of AR (*1*).

Crumb rubber chip seal is the spray applications of rubber modified binder, which has demonstrated unique advantages over traditional chip seal applications. Nationwide, crumb rubber chip seals have two different CRM percentages, less than 10% and about 20%. The higher percentage product is called AR chip seal based on the ASTM standard (*2*). The AR chip seal is very effective in preventing reflective cracking from the existing pavement. It normally has longer life and less maintenance than the conventional chip seals. It has a higher application rate of 0.55 to 0.65 gal per square yard, which makes it more durable against oxidation. Most AR chip seal will last longer than conventional chip seal if applied in similar conditions.

Warm-mix asphalt (WMA) is the name given to certain technologies that reduce the production and placement temperatures of asphalt mixes (*3*). Generally, the production and placement temperatures should be between 185°F (85°C) and 275°F (135°C) for an asphalt to be considered

WMA (*4*). There are a wide range of benefits that are reported by using WMA. Reduced fuel usage and emissions are the two major benefits. Other benefits that have been reported include compaction aides, longer paving season–hauling distances, and improved working conditions (*4*). While there is not a range of established values for fuel reduction, of the WMA projects monitored, fuel savings of 20% to 35% are possible (*3*). The level of emission reduction varies upon several factors including the degree of temperature reduction, aggregate moisture content, and reclaimed asphalt pavement usage (*4*).

OBJECTIVES

The objectives of this paper are to evaluate the feasibility of using warm-mix technologies for AR chip seals or other seal coats involved with AR to determine whether these technologies will allow operations at lower temperatures without harming the performance, as well as reduce the emission and odor of the AR spray applications.

ASPHALT RUBBER WITH WARM-MIX TECHNOLOGIES

AR has been used in asphalt mixes since as early as the mid 1960s when it was pioneered by the City of Phoenix, Arizona, to be used in their chip seal program for the city's streets. Since the Arizona Department of Transportation (DOT) fully implemented their rubber asphalt program in 1988, they have used more than 4.2 million tons of AR which results in the recycling of 15 million old tires (*5*). When implementing crumb rubber into the asphalt, the increased flexibility of the pavement has reduced the cracking by an estimated 20% (*6*). Given the benefits of using rubber asphalt, there are qualities that make it less attractive to utilize. Inserting rubber into the asphalt reduces the workability of the mixture. This, in turn, results in higher mixing and compaction temperatures to achieve the desired workability (*7*). AR production can also only be limited to 1,000 tons per day in some areas because of the restriction for maximum allowable emissions (*8*).

However, with the implementation of right warm-mix technologies, these problems can be solved without significant issues. Both the production and application temperatures of AR can be reduced considerably. While the temperatures of rubberized WMA spray applications are outside of the definition of WMA, 185°F (85°F) and 275°F (135°C), the warm-mix technology helps reduce the odor and smoke coming from the AR. This helps cut the cost of the burner fuel (due to reduced usage of fuel) and reduces the emissions, allowing more AR to be produced without exceeding the maximum allowable emissions.

SUMMARY OF PROJECTS USING WARM-MIX TECHNOLOGIES WITH AR SPRAY APPLICATIONS IN CALIFORNIA

California began trials of using warm-mix additives with AR spray applications in 2010. The projects were constructed by the California DOT (Caltrans) and local agencies in California. Table 1 lists some selected projects that have been applied during 2010 and 2011. Figure 1 shows the locations of these projects. California Pavement Preservation Center (CP2) has been monitoring the construction and performance of these projects.

TABLE 1 Selected AR Spray Applications with Warm-Mix Technologies in California

Road Name	Location (PM: n/n)	Date Constructed	WMA
North Cirby St.	City of Roseville	June 2010	Sasobit
Smith Ave.	Los Angeles County	August 2010	Engineered additives WMA
I-5	Near Firebaugh, Fresno County (PM 37.2–45.0)	September 2010	Engineered additives WMA
Various city streets	City of Roseville	September–October 2010	Engineered additives WMA
SR-150	Near Vertura, SR-150 (PM 0.0–11.0)	August 2011	Sasobit GTR-850
Various city streets	City of Lodi	September 2011	Sasobit GTR-850
Various city streets	City of Fort Bragg	August–September 2011	Sasobit GTR-850

FIGURE 1 Location of California AR spray applications with WMA.

City of Roseville, June 2010

A 1,000-ft test section was constructed with a double chip seal on North Cirby Street in the city of Roseville. The first chip application consisted of a 3/8-in. precoated aggregate on 0.55 gal/yd^2 of AR binder treated with WMA Sasobit. The top layer chip seal consisted of finer 1/8-in. precoated rock with PG 76-22 TR binder. The application rate of the PG 76-22 is 0.23 gal/yd^2. Figure 2 shows the spray application of AR at temperature of 350°F. The level of smoke and odor was greatly reduced.

This is the first time that an AR chip seal with warm-mix Sasobit was placed in California or perhaps elsewhere. The project was revisited in September 2011 by the CP2 Center and the current condition is shown in Figure 3. The existing pavement had many cracks before the construction. However, there were no reflective cracking coming through the pavement during the latest inspection. There were some light bleeding issues along the wheelpaths due to school buses, but they were not significant.

FIGURE 2 Spray application of AR binder at reduced temperature.

(a)

(b)

FIGURE 3 The visual inspection of pavement condition of North Cirby project after 1 year: (*a*) North Cirby Street completed project, June 2010, and (*b*) North Cirby Street, September 2011.

Los Angeles County, August 2010

The Los Angeles County Department of Public Works placed an AR chip seal project on Smith Avenue in the unincorporated community of Acton in August 2010. The application rates for the AR warm-mix binder were between 0.6 and 0.66 gal/yd^2. The placement temperature of the AR warm-mix binder was 335°F. The warm-mix additive is engineered additives WMA and was blended at 1.5% by weight of the AR binder. The chip was a 3/8-in. precoated aggregate and spread at 32 to 34 lbs/yd^2. Figure 4 shows the construction process. There was significantly less smoke comparing with no warm-mix conventional AR chip seal applications. After the chip seal, a Type II microsurfacing was placed over in September 2010.

The performance of the cape seal consisting of AR chip seal and microsurfacing were monitored after the construction. In fall 2010 cracks developed on the surface due to unseasonable cold temperatures. In July 2011, cores were taken and pavement conditions were re-evaluated. Five of six cracks in the edge of cores did not reflect through the AR chip seal layer although the microsurfacing layer contained many cracks. Figure 5 shows the cross-section views of some cores. This demonstrated the crack resisting ability of AR chip seals.

I-5 near Fresno, September 2010

Caltrans constructed a test strip in District 6 on I-5 from PM 37.2 to PM 45.0 on the 5-ft wide northbound shoulder. The existing asphalt concrete shoulder was exhibiting weathering and some transverse cracks shown in Figure 6. The pavement temperature started with the 90s and

(a) **(b)**

FIGURE 4 Spray of AR binder: (*a*) rock spreader and (*b*) compaction.

FIGURE 5 Cross-section view of cores taken from the Los Angeles County project.

FIGURE 6 Prepavement condition of I-5 AR chip seal project.

dropped to 75°F at midnight. The AR binder application rate was 0.6 gal/yd^2. The binder application temperature was 340°F. The binder was covered with 3/8-in. hot precoated chips with temperature of 300°F when spread. The surface of the finished job was uniform. The adhesion between the rock and binder are very good. A photo of the finished job is shown in Figure 7. The District 6 warm-mix AR chip seal project has substantially less emissions when compared to a conventional AR chip seal because of almost 60-degree temperature reduction. The performance of this project after 1 year is very good. There are no distresses showing up in 2011.

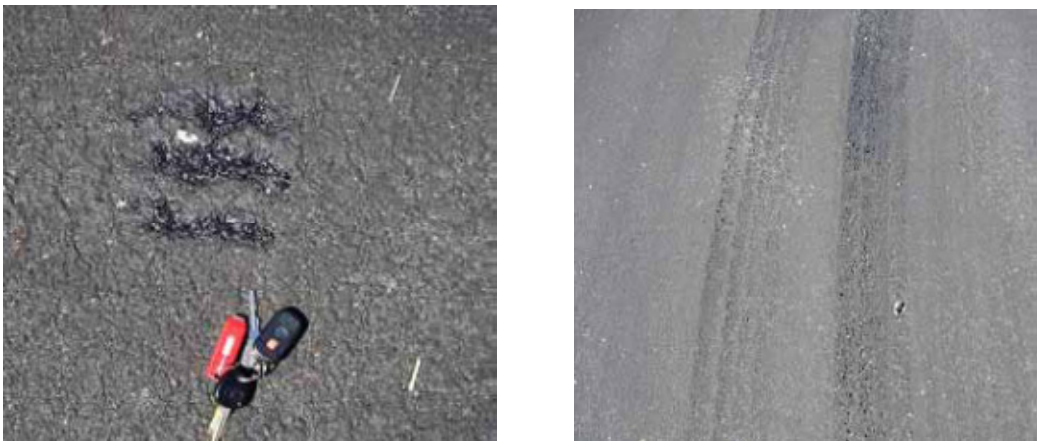
City of Roseville, September to October 2010

From the end of September to the middle of October, the City of Roseville paved the various local residential streets with a double chip seal. The existing pavements in this area were about 25 years old and had not received any major maintenance. The city first did some repairs on the existing pavement with some dig outs and skin patches where there was rutting or extreme alligator cracking. The double chip seal consisted of two layers. The first layer was a polymer-modified AR (including both warm-mix additives and polymers) chip seal with 3/8-in. precoated hot applied chips. The warm mix was added and mixed with the AR binder on a mixing truck with internal agitation. The second layer was a modified binder seal coat using PG 76-22 TR and 1/8-in. precoated hot applied chips. The PMAR warm-mix binder was applied at a rate of 0.60 gal/yd^2 and at about 340°F shown in Figure 8. The second layer was applied at a rate of 0.25 gal/yd^2. The warm-mix additive was a wax type product provided by Engineered Additives.

FIGURE 7 Completed AR with warm-mix chip seal project on I-5.

FIGURE 8 Application of AR binder with warm-mix engineering additive.

The project went down smoothly and without any problems. However, during the hot summer of 2011, some problems with the double chip seal appeared primarily in cul-de-sacs and turning locations of the treated residential streets. Soft spots, bleeding, and wheel tracks showed up under the valley hot summer temperatures shown in Figure 9. The pavement temperatures in the Sacramento Valley can easily reach 140°F in the summer. For the double chip seals, especially in the cul-de-sacs and street corners, a binder content with more than 1.5 gal/yd^2 of oil per square yard can be applied due to overlapping spray applications from the distributer truck. This could cause bleeding and soft pavement problems due to the high binder application rate. The project was repaired with addition of a blotter of Portland cement followed by a slurry seal shown in Figure 10.



(a) (b)

FIGURE 9 Double chip seal project problems at cul-de-sac locations: (*a*) excessive binder and soft spots in cul-de-sacs and (*b*) tearing of soft mat under turning traffic.

FIGURE 10 Cul-de-sac Scott Mills Court after slurry seal repair in October 2011.

AR WARM CHIP SEAL PROJECTS IN 2011

Realizing the potential benefits of using warm mix with AR spray applications, four new demonstration projects were constructed during the 2011 season. Caltrans placed a conventional and warm-mix AR chip seals on SR-150 near Ojai in August 2011. Both products were placed at night and performed well. The placement temperature for the warm mix was 340°F compared with the conventional AR chip seal which was placed at 390°F. The City of Fort Bragg placed a cape seal using warm-mix AR chip seal for the first application followed by a Type II slurry seal in August–September 2011. A number of streets in the city were treated using this technique and the results appeared to be very good. The City of Lodi completed a cape seal in the summer of

2011. The cape seal consisted of a WMA rubber chip seal followed by a Type II slurry. The project went down well and the city was satisfied with the initial performance of the product. Figure 11 shows the finished products of the three AR chip seal with warm-mix projects in California. The long-term performance of these projects will be monitored and documented.

CONCLUSIONS AND RECOMMENDATIONS

AR chip seal has been used in the asphalt industry since the mid-1960s. Over the years, the industry has recycled millions of old tires by using them in the asphalt, saving them from taking up valuable space in our landfills. Rubber has been more expensive to incorporate in the mix

(a) **(b)**

(c)

FIGURE 11 Three new warm-mix AR seal coat projects constructed in 2011 in California: (*a*) warm-mix AR on SR-150 near Ojai; (*b*) warm-mix AR cap seal in Fort Bragg; and (*c*) warm-mix AR cape seal in Lodi.

design of asphalt because it requires a higher temperature to obtain the desired workability. However, it has been discovered that by adding a WMA additive to the mix design, the paving temperatures are reduced without compromising the production rates. While the temperatures aren't reduced as much as a WMA devoid of rubber, the temperatures can be reduced to a range that makes the use of rubber more cost-effective and environmentally greener.

CONCLUSIONS

The results from this study suggest the following beneficial conclusions are warranted:

- Warm-mix technologies can be used with AR chip seals. They allow the mixes to be placed at night and in cooler climates.
- Warm-mix technologies can significantly lower the hot applied AR chip seal application temperatures, which produce lower emissions at the job site.
- Warm-mix technologies can improve workers' working conditions. They reduce undesired AR odor and blue smoke coming with regular AR seal coat job.
- Warm-mix technologies can reduce fuel usage because it reduces the production temperatures by 40°F to 60°F. They have energy saving benefits for AR mixes.
- By reducing emission at both production and paving procedures by warm mix, the carbon footprint and greenhouse gas conditions can be improved.
- The warm-mix AR chip seals offer agencies a maintenance treatment for cracked and aged pavements that has a lower construction cost than a 1-in. thin blank HMA overlay and faster construction.
- The construction time for a warm-mix AR chip seal is much shorter than for a 1-in. thin blanket HMA overlay and is less disruptive to the motorists and adjacent residents.
- Depending on the actual temperature reduction of the product, the warm-mix alternatives may offer as much as an 80% emission savings, plus a sizable energy savings. This emission reduction may equate to huge cost savings in permit fees paid to air quality control agencies.

The following are the disadvantages of a warm-mix seal coat:

- Excessive chips were left on the sidewalk, lawn, and driveway for a residential street project. This can be avoided by the contractor to use some labors to clean the drive way and sidewalks after the chip seals.
- The long-term performance of warm-mix AR chip seals is still unknown. The initial performance showed that it can resist reflective cracking very well. Long-term performance still needs to be studied.
- For cul-de-sac and turning locations, double chip seals contained too much binder and showed bleeding and soft mat under extreme hot weather conditions.

RECOMMENDATIONS

Based on the findings to date, the following recommendations are appropriate:

- More trials should be constructed for using warm-mix technologies for spray applications with AR and terminal blends.
- Double chip seals contained too much binder at cul-de-sac and turning locations because of spray overlapping. A slurry seal or thin HMA overlay may be a better solution for the cul-de-sac situation.

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ISSUES IN PAVEMENT PRESERVATION AND MAINTENANCE

Partnering in Maintenance Management
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MILTON THACKER
DBi Services

DBi Services provides comprehensive asset operations and maintenance for the Woodrow Wilson Bridge corridor in the Washington, D.C., area, including the maintenance of approach roadways and interchange ramps. This project also includes the inspection, maintenance, and operations of the Woodrow Wilson Bridge itself, along with 41 highway grade-separation structures on the Maryland approach and 40 bridges and culverts on the Virginia approach, as well as winter operations. DBi Services is also responsible for the opening of the drawbridges for marine traffic and the maintenance of all of mechanical and electrical components on the bridge. This project is the first asset management contract of its kind, encompassing two states, Washington, D.C., and two highway agencies. It consists of approximately 11 centerline miles and 106 lane miles as part of the contract. DBi Services is responsible for overseeing all assets within the project limits from beginning to end, with the Virginia Department of Transportation and the Maryland State Highway Administration having oversight responsibility. Construction of the bridge began in 2000 and took more than 9 years to complete at a cost of more than $2.5 billion. The bridge carries the inner and outer loops of the Capital Beltway (I-495 and I-95) and a 12-ft wide bicycle–pedestrian trail between Alexandria, Virginia, and Prince George's County, Maryland. The Woodrow Wilson Bridge is the largest bascule span drawbridge in the world, with a movable span length of 370 ft and 6,075 ft overall structure length. The average daily traffic on the bridge is 200,000 vehicles per day. DBi Services is the first asset management contractor to conduct operations, maintenance, and National Bridge Inspection Standards inspections of this extraordinary asset. The 106 lane mile project corridor consists of I-495, I-95, and I-295 and is extremely complex. DBi Services' responsibilities include management, inspection, highway and bridge maintenance, roadside maintenance, and repair of traffic appurtenances, tending and operation of the drawbridge spans, highway, aesthetics, and navigational lighting, and intelligent transportation system devices as well as accident and emergency response, customer service, and snow and ice control throughout the project corridor. This unprecedented project involves the need for partnering, communication, and coordination across multiple agencies. This presentation focuses on how this communication is accomplished and how agencies can work together successfully to meet the day-to-day challenges posed in fulfilling the maintenance needs of this project.

ISSUES IN PAVEMENT PRESERVATION AND MAINTENANCE

Optimization Model for Pavement Maintenance Planning and Resource Allocation

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Pavement management systems are widely used and are continuously being improved because they can lead to considerable fund savings and to higher levels of service of road pavements. In this work, a model for pavement maintenance, rehabilitation planning, and optimal resource allocation is presented. The objective function aims at minimizing a generalized cost parameter that includes (1) agency cost; (2) user costs (including vehicle operating cost for fuel consumption, vehicle maintenance and depreciation, travel delay cost, accident cost, discomfort cost); and (3) environmental cost due to pavement deterioration. The maintenance and rehabilitation treatments are considered with regard to their cost and effectiveness characteristics. Besides the pavement condition deterioration functions, which are represented by the PSI (present serviceability index), other constraints of the model include budgetary availability, threshold values for the minimum accepted pavement condition levels, desirable pavement condition levels, maintenance and rehabilitation treatment applicability, and effectiveness. Due to the size and complexity of the problem, a genetic algorithm has been used as an optimization tool. The optimization runs over several road sections with different traffic and pavement condition characteristics and within a time span defined by the user. The budgetary or the minimum accepted pavement condition constraints can be altered to get a Pareto-front set of optimal solutions for a particular application. The application presented indicates that the model provides reasonable results in terms of the appropriate selection of maintenance and rehabilitation treatments and the time of application.

In recent years the focus of the transportation authorities, researchers and practitioners is being shifted from the construction of new roads to the management of existing road structures and especially to road pavements. Road management requires a large investment in order that the public agencies maintain and manage these infrastructures effectively. However, effective management would yield a safe environment for public users and protection to nature.

Planning and managing activities for a large network of transportation infrastructure is a daunting task. Many projects and interests compete for the limited resources allocated to a transportation agency and infrastructure management is only one of such competing interests. How much resources to allocate to transportation infrastructure and how to get the best value for the allocated resources have received high priority by top management officials of these agencies. The decision makers who have to make these types of choices often do so based on a number of criteria. Such criteria include limited budget for capital and recurrent expenditure, the need to keep the transportation network open at an acceptable level of service, etc.

Pavement management in a broad sense includes all the activities contained in the planning, design, construction and rehabilitation of a pavement. Recommendations for pavement maintenance include: selection of alternative treatments, present serviceability of the pavement,

likely performance of alternative treatments, required life of pavement, costs, effects on traffic flow, effects on road user, availability of resources. That is why alternative strategies, cost and life of each strategy, and a pavement management system are desirable for effective development of pavement maintenance strategies.

Pavement maintenance strategies are closely related to and a component of pavement management systems (PMSs). PMS is a set of defined procedures for collecting, analyzing, maintaining, and reporting pavement data, to assist the decision makers in finding optimum strategies for maintaining pavements in serviceable condition over a given period of time for the least cost. While a PMS cannot make final decisions, it can provide the basis for an informed understanding of the possible consequences of alternative decisions. The main components of a PMS are the models used to predict pavement performance and the approach used to select the maintenance and rehabilitation strategy (taking into account the expected pavement deterioration).

BACKGROUND

A PMS is designed to provide objective information and useful data for analysis so that road managers can make more consistent, cost-effective, and defensible decisions related to the preservation of a pavement network. Management systems were originally designed in the 1970s as a result of significant work on roadways in the United States and Canada. Initially, pavement management focused on the project level, coordinating improvements in design, restoration, maintenance, and behavior of the model of the surface. Subsequently, PMSs expanded their use at network level, participating in the design, planning, and allocating resources throughout the network of roadways.

In 1976, a PMS is constructed based on economic analysis by linear programming (*1*). The system takes into account the current condition of the network and the expected service life and creates a list of pavements that are indentified as candidates for rehabilitation. Every pavement is forecasted and evaluated with alternative strategies. Until 1982, other methods, behavior curves, and mathematical models are used to identify the optimal solution for pavement maintenance and rehabilitation.

During the 1980s, and particularly after the North American Pavement Management Conference held in Toronto, Canada, in 1985, PMSs are recognized to be a major tool to aid the road engineer. In the same period the development of artificial intelligence and its application to pavement management problems begin and PMSs use expert or fuzzy systems, neural networks, and genetic algorithms to identify the optimal solution for maintenance. In particular, genetic algorithms are widely used because of their capacity to deal with complex engineering optimization problems, and are recognized as the most useful method of artificial intelligence in pavement management.

Fwa et al. (*2*) develop a computer model based on genetic algorithm to solve the network-level pavement management problem. The user enters the objective function that wishes to optimize giving the appropriate parameters and modifying slightly the code of the algorithm. This model demonstrated the easy adaptation of genetic algorithms in pavement management problems but was not used any further.

The Australian Defence Force Academy (*3*) developed a pavement management model based on genetic algorithms that considers agency cost and user vehicle operation cost for life cost analysis. The system proposes for each segment of the pavement an annual maintenance cost and

identifies the optimal time period for the next treatment. The model can be extended to incorporate political feedback.

Ferreira et al. (*4*) introduced a system that minimizes the cost of road maintenance and recommends the best pavement treatment. The system is based on a deterministic model for pavement deterioration. Furthermore, the system uses a genetic algorithm and exports the results on a map through geographic information system model. In this system, only agency cost is calculated and since the programming language and the design of the system are quite outdated, the system needs enough time to define the optimal solution. Morcous and Lounis (*5*) expand the research of Fereira and his team by using probabilistic models for pavement deterioration and by applying the system in bridges pavements.

Herabat and Tangphaisankun (*6*) use a genetic algorithm for the construction of a PMS for Thailand's road network. The system uses linear models based on the international roughness index (IRI) and obtains five alternative strategies for pavement maintenance. The model considers traffic as the only factor to influence pavement distress and identifies the optimal solution minimizing vehicle operation cost.

Bosurgi and Trifiro (*7*) developed a PMS based on genetic algorithms that investigates the best solution for pavement maintenance with an initial standard budget. The pavement performance model is linear based on present serviceability index (PSI). The system receives a limited number of alternative treatments and does not calculate total user cost.

From the literature review, it is shown that genetic algorithms are widely used in PMSs to identify the maintenance solution which minimizes agency cost. Few systems deal with user costs and these consider mainly vehicle operation cost. In this paper a PMS is developed that can be used by decision makers to define the optimal solution for pavement maintenance. The system (Paveman) is based on genetic algorithms and minimizes the generalized cost (agency cost, user costs, and environmental cost) while keeping the road condition in high levels. Finally, the program, unlike previous attempts, has an unlimited number of maintenance strategies and it is made in a new programming language using the latest technologies, therefore achieving better computational results.

OPTIMIZATION MODEL

Several PMSs are in use by many transportation agencies. There are two types of management systems, those that are driven by optimization models and those that rely on expert (knowledge) systems. As transportation networks become larger and larger, it becomes imperative that some form of optimization modeling is needed. The majority of such optimization models are of the type where a single objective is optimized. In reality, however, transportation officials are faced with multiple objectives or criteria that need to be traded off before a final decision is reached.

The model presented in this article investigates the optimal solution for a time period defined by the user. The system proposes a maintenance strategy for every year of the analysis period and for each pavement segment. The optimal solution must satisfy three objectives:

- The total agency cost for all the pavement segments do not exceed the initial budget which is defined by the user;
- The generalized maintenance cost (agency cost, user costs due to pavement deterioration and cost to the environment) is minimized; and

- Pavement condition is maintained for all segments and throughout the whole analysis period in high levels.

Objective Function

The objective function consists of two parts, the second part satisfies the first two criteria from above (cost part) and the first part satisfies the third objective (pavement condition part). The optimal solution maximizes the objective function, which is defined as follows:

$$F = \max\left[R + a\left(\frac{M - \mathrm{Psi_{av}}}{(S \cdot T)^2}\right) + b\left(\frac{B - Ca}{C\mathrm{gen}}\right)\right] \tag{1}$$

$$R = \begin{cases} 1, & \text{if } C_a \leq B \\ 0, & \text{if } C_a > B \end{cases} \tag{2}$$

$$s = 1, \ldots, S \text{ and } t = 1, \ldots, T \tag{3}$$

$$M = \sum_{s=1}^{S} \sum_{t=1}^{T} m \tag{4}$$

$$m = \begin{cases} 1, & \text{if } \frac{\mathrm{Psi_{st}} - \mathrm{Psi_{end}}}{2} \geq \mathrm{Psi_{min}} \\ 0, & \text{if } \frac{\mathrm{Psi_{st}} - \mathrm{Psi_{end}}}{2} < \mathrm{Psi_{min}} \end{cases} \tag{5}$$

$$\mathrm{Psi_{av}} = \sum_{s=1}^{S} \sum_{t=1}^{T} \frac{\mathrm{Psi_{st}} - \mathrm{Psi_{end}}}{2} \tag{6}$$

$$C_a = \sum_{s=1}^{S} \sum_{t=1}^{T} c_{\mathrm{tr}} \tag{7}$$

$$C_{\mathrm{gen}} = C_u + C_{\mathrm{env}} + C_a \tag{8}$$

$$C_u = \sum_{s=1}^{S} \sum_{t=1}^{T} c_u \tag{9}$$

$$C_{\mathrm{env}} = \sum_{s=1}^{S} \sum_{T=1}^{T} c_{\mathrm{env}} \tag{10}$$

where

F = objective function;
c_{tr} = treatment cost for segment s in year t;
S = number of road segments;
T = number of years in the planning time span;
B = initial budget;
C_a = agency cost for all the segments in the analysis period;
R = factor which increments by one unit the value of the equation if the agency cost is less than the initial budget;
a and b = coefficients which take values from 0 to 1 depending on the weight given on each part of the objective equation (Pareto method);

c_u = user cost for segment s in year t;
c_{env} = cost to the environment for segment s in year t;
C_u = total user cost for all the segments in the analysis period;
C_{env} = total cost to the environment for all the segments in the analysis period;
C_{gen} = generalized maintenance cost for all the segments in the analysis period;
Psi_{min} = minimum acceptable pavement condition;
Psi_{st} = initial pavement condition for segment s in year t;
Psi_{end} = final pavement condition (after the treatment) for segment s in year t;
Psi_{av} = average pavement condition for all the segments in the analysis period;
m = factor which adds one unit for every segment in each year of the time span when the average pavement condition is better than the minimum acceptable one; and
M = sum of m for all the segments in the analysis period.

Pavement Condition Functions

PMSs should include modules to predict the behavior of pavements. Pavement performance models employed within a PMS may be deterministic or probabilistic. Deterministic models use regression equations to describe the evolution of pavement condition over time, whereas probabilistic models use Markov chains for the same purpose. In this paper, a deterministic model is developed because deterministic models describe pavement performance in detailed, quantitative terms, with reference to the different types of distresses (cracking, rutting, etc.) that characterize pavement condition.

Since the use of distinct performance models for each distress types does not add substantial value to the decision process of this system, it is decided to use a generalized model for evenness, which has been developed earlier by our team (*8*). The model is based on expert opinions and fuzzy systems considering pavement related and traffic parameters. The distress index is

$$DI_{even} = 7.584\ AGE^{1.265}\ MSN^{-0.844}\ TRAF^{0.2185}\ QUA^{-0.253} \tag{11}$$

$$MSN = 0.0394\ (b_1 d_1 + b_2 d_2 + b_3 d_3) + SNSG \tag{12}$$

$$d_1 = d_{11} + d_{12} + d_{13} \tag{13}$$

$$b_1 = -8\ 10^{-13}\ psi_{asphalt}{}^2 + 10^{-6}\ psi_{asphalt} + 0.0904 \tag{14}$$

$$psi_{asphalt} = 145\ E_{asphalt} \tag{15}$$

$$b_2 = 0.249\ \log(psi_{base}\ m_2) - 0.977 \tag{16}$$

$$psi_{base} = 145\ E_{base} \tag{17}$$

$$b_3 = 0.277\ \log(psi_{subbase}\ m_3) - 0.839 \tag{18}$$

$$psi_{subbase} = 145\ E_{subbase} \tag{19}$$

$$\text{SNSG} = 3.51 \log(\text{CBR } m_4) - 0.85 [\log(\text{CBR } m_4)]^2 - 1.43 \quad (20)$$

$$\text{CBR} = E_{\text{subgrade}}/10 \quad (21)$$

$$\text{TRAF} = \left(\frac{Q}{365}\right) \times \left(\frac{1}{n}\right) \text{TR} \quad (22)$$

where

SNSG = parameter for the contribution of soil on structural strength of the pavement,
CBR = California bearing ratio (%),
d_{11} = thickness of the asphalt overlay (mm),
d_{12} = thickness of the binder layer (mm),
d_{13} = thickness of the base layer (mm),
d_1 = thickness of the surface layer (mm),
d_2 = thickness of the base (mm),
d_3 = thickness of the subbase (mm),
E_{asphalt} = modulus of elasticity of the surface layer (MPa),
E_{base} = modulus of elasticity of the base (MPa),
E_{subbase} = modulus of elasticity of the subbase (MPa),
E_{subgrade} = modulus of elasticity of subgrade (MPa),
m_2 = factor that indicates moisture to the base (%), m_3 is a factor that indicates moisture to the subbase (%),
m_4 = factor that indicates moisture to the subgrade (%),
Q = annual average traffic flow (vehicles/year),
TR = truck ratio (%),
n = number of lanes of the road segment which is examined,
AGE = pavement age initiating from last construction (in years),
MSN = structural strength parameter,
TRAF = traffic load parameter, and
QUA = construction quality parameter that takes values from 0 to 10 (10 represents good construction quality, 0 represents bad quality).

The evenness index (DI_{even}) is a dimensionless parameter which is valued from 0 to 100, where 0 represents the excellent pavement condition (no distresses) and 100 represents the poorest pavement situation (maximum severity of distresses, pavement failure). The correlation of the evenness index with the PSI is calculated as follows:

$$\text{PCI} = 100 - \text{DI}_{\text{even}} \text{ (values from 100 to 0)} \quad (23)$$

$$\text{PSI} = \text{PCI} / 20 \quad (24)$$

The PSI combines information from all distress types, severity, and extent into a single number. This number can be used at the network level to define the pavement condition (driving quality), to identify when treatments are needed, for ranking or prioritization, and as a number used to forecast pavement condition. The index values from 0 (unacceptable driving quality) to 5 (excellent driving quality). PSI values decrease gradually with time. The value 2.5 is usually

considered as a warning level for maintenance of the pavement. When PSI index values less than 2.0, the pavement segment is considered in poor condition and requires immediate rehabilitation.

Agency Cost

The maintenance of pavements can be done with various alternative treatments. The treatments present a large diversity in regard to suitability of intervention, materials and equipment used, and unit cost. The maintenance strategies are evaluated based on their cost and effectiveness. As treatment efficiency can be considered pavement life after maintenance, which depends on the treatment type and the traffic volume of the road segment. As a result, it is desirable to define different lifetime for the three levels of traffic flow (low, medium, high).

In the system developed in this work, a number of maintenance strategies are considered (Figure 1). The user is further able to add other maintenance strategies if necessary. Each treatment is associated with a unit cost and an expected pavement life after maintenance. Unit costs consist of expenses for materials, machinery and manpower required to maintain a square meter of the pavement surface. The unit cost may be adjusted by the user if necessary.

User Costs

Traffic is directly related to the development of the national economy of a country and is the main reason for pavement deterioration and its impact on the cost of users. The best way to reduce the cost of users is to maintain the road at higher condition levels. PMSs typically optimize maintenance costs but do not compute the cost of users because it is difficult to be assessed.

Manage Treatment Types

Save | Load Defaults

Name	Cost Per Square Meter	Low Traffic Flow - Lifetime	Medium Traffic Flow - Lifetime	High Traffic Flow - Lifetime
Local laying of hot or cold asphalt, preceded by adhesion.	2.93	1.50	1.00	0.70
Local purge without squaring and laying of hot or cold asphalt, preceded by adhesion.	4.11	2.50	1.50	1.00
Local purge with squaring and laying of hot or cold asphalt, preceded by adhesion.	7.34	5.00	3.50	2.50
Local purge without squaring and laying of hot or cold asphalt, preceded by adhesion and leveling with a 4-5 cm layer.	8.22	6.00	4.50	3.50
Local purge with squaring and laying of hot or cold asphalt, preceded by adhesion and leveling with a 4-5 cm layer.	10.27	8.00	6.50	5.00
Local laying of hot or cold asphalt, preceded by adhesion and leveling with a 4-5 cm layer.	7.04	4.50	3.00	2.00
Local purge with squaring and laying of hot or cold asphalt, preceded by adhesion, leveling with a 4-5 cm layer and ant...	17.31	16.50	14.00	12.50
Miling in layers and leveling with a 4-5 cm layer.	9.10	7.00	5.50	4.00
Miling in layers and leveling with a 4-5 cm layer and then anti-slip matting.	14.97	13.00	10.50	9.00
Crack filling with asphalt paste.	2.35	1.00	0.60	0.40
Crack filling with aggregate-asphalt or other synthetic materials.	2.64	1.20	0.80	0.60
Crack filling with aggregate-asphalt or other synthetic materials and leveling with a 4-5 cm layer.	6.75	4.00	3.00	2.00
Contruction of a leveling layer.	4.40	2.50	1.70	1.20
Anti-slip matting.	8.60	5.00	4.20	3.50
Contruction of a leveling layer and anti-slip matting.	10.56	7.50	6.50	5.50
Laying - scattering fine aggregate.	4.40	2.50	2.00	1.00
Reconstruction.	19.00	19.00	16.00	14.00
	0.00	0	0	0

FIGURE 1 Maintenance and rehabilitation strategies of the system.

User cost consists of four main components. These components are the vehicle operation cost, accident cost, travel delay cost, and discomfort cost. Vehicle operation cost consists of cost for fuel consumption, vehicle maintenance, and depreciation.

Vehicle Operation Cost

Vehicle operation cost is directly dependent on the smoothness of the pavement surface. An important element in vehicle operation cost is the type of vehicle and for this reason the cost varies depending on vehicle type (heavy vehicles or passenger cars). The cost for vehicle maintenance consists of the cost for vehicle parts and the cost of labor hours for maintaining a vehicle. The cost for depreciation and the cost for vehicle maintenance in relation to pavement condition are calculated as follows (*9*):

$$C_{\text{depr(PC)}} = (0.0052\ \text{PSI}^2 - 0.0368\text{PSI} + 0.1067)\ L \tag{25}$$

$$C_{\text{depr(HT)}} = (0.0021\ \text{PSI}^2 - 0.0153\text{PSI} + 0.0459)\ L \tag{26}$$

$$C_{\text{parts(PC)}} = \frac{1.3852}{100000}\ e^{-0.699\ \text{PSI}}\ \text{P}_{\text{PC}}\ L \tag{27}$$

$$C_{\text{parts(HT)}} = \frac{0.5428}{100000}\ e^{-0.472\ \text{PSI}}\ P_{\text{HT}}\ L \tag{28}$$

$$\text{C}_{\text{work(PC)}} = 4.563\ e^{-0.204\ \text{PSI}}\ W \frac{\text{L}}{1000} \tag{29}$$

$$C_{\text{work(HT)}} = 26.864\ e^{-0.245\text{PSI}}\ W \frac{L}{1000} \tag{30}$$

where

$C_{\text{depr(PC)}}$ = cost for depreciation of a passenger car (€/vehicle);
$C_{\text{depr(HT)}}$ = cost for depreciation of a heavy vehicle (€/vehicle);
PSI = pavement condition index;
L = length of the road segment (km);
$C_{\text{parts(PC)}}$ = cost for parts for a passenger car (€/vehicle);
$C_{\text{parts(HT)}}$ = cost for parts for a heavy vehicle (€/vehicle);
P_{PC} = average price of a typical passenger car (€);
P_{HT} = average price of a common heavy vehicle (€);
$C_{\text{work(PC)}}$ = cost of labor hours for maintaining a passenger car (€/vehicle);
$C_{\text{work(HT)}}$ = cost of labor hours for maintaining a heavy vehicle (€/vehicle); and
W = average hourly worker salary (€/hour).

Fuel cost because of pavement deterioration is given as follows:

$$C_{\text{fuel}} = -\frac{L}{1000}\ [0.1548\ \text{TR} \times P_d + 0.0846\ (1 - \text{TR}) \times P_{\text{un}}]\ \ln\ (0.2\ \text{PSI}) \tag{31}$$

where C_{fuel} is the fuel cost due to pavement deterioration (€/vehicle), TR is the truck ratio (%), P_d is the average diesel price (€/lt), and P_{un} is the average petrol price (€/lt).

Accident Cost

The cost of accidents is hard to assess and this is because it is difficult to value human life. Accidents happen due to various causes, the most important of which are human factors, while the contribution of pavement condition is not as high but also not negligible. The number of accidents that may be considered as having their origin to pavement condition is calculated by the following equation (*10*):

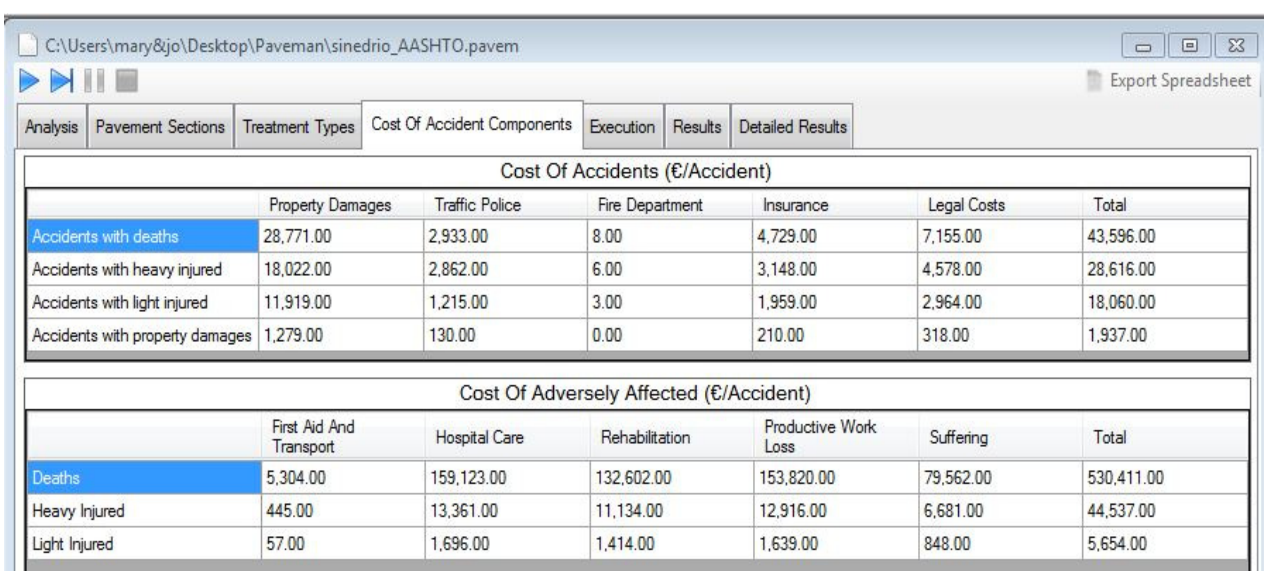
$$E_a = \frac{L}{16.09344}\, e^{[-4.070 + 0.655 \ln\left(\frac{Q}{365}\right) - 0.345\ \text{PSI}]} \tag{32}$$

where E_a is the number of accidents in 1 year due to pavement condition (accidents/year) and Q is the annual average traffic flow (vehicles/year).

The cost of accidents is determined by the values of the cost components of an accident which are obtained in the system as shown in Figure 2. These values can be set up by the user of the system if this is necessary.

Travel Delay Cost

Travel delay cost due to pavement condition may be practically considered if pavement condition drops below the alarm threshold (PSI ≤ 2). If pavement condition varies in the range 1 < PSI ≤ 2 and pavement segments are parts of urban roads, then travel delay cost is negligible. Otherwise travel delay cost is calculated (on the basis of data provided in *9*) as follows:



Cost Of Accidents (€/Accident)

	Property Damages	Traffic Police	Fire Department	Insurance	Legal Costs	Total
Accidents with deaths	28,771.00	2,933.00	8.00	4,729.00	7,155.00	43,596.00
Accidents with heavy injured	18,022.00	2,862.00	6.00	3,148.00	4,578.00	28,616.00
Accidents with light injured	11,919.00	1,215.00	3.00	1,959.00	2,964.00	18,060.00
Accidents with property damages	1,279.00	130.00	0.00	210.00	318.00	1,937.00

Cost Of Adversely Affected (€/Accident)

	First Aid And Transport	Hospital Care	Rehabilitation	Productive Work Loss	Suffering	Total
Deaths	5,304.00	159,123.00	132,602.00	153,820.00	79,562.00	530,411.00
Heavy Injured	445.00	13,361.00	11,134.00	12,916.00	6,681.00	44,537.00
Light Injured	57.00	1,696.00	1,414.00	1,639.00	848.00	5,654.00

FIGURE 2 Accident parameter values in the system.

$$C_{\text{delay(PC)}} = \frac{L \times W}{0.5779\ \text{PSI}^2 + 40.454\ \text{PSI} + 31.674} \tag{33}$$

$$C_{\text{delay(HT)}} = \frac{L \times W}{18.981\ \text{PSI}^2 + 3.5838\ \text{PSI} + 39.056} \tag{34}$$

where $C_{\text{delay(PC)}}$ is the travel delay cost of a passenger car (€/vehicle), $C_{\text{delay(HT)}}$ is the travel delay cost of a heavy vehicle (€/vehicle), and W is the average hourly worker salary (€/hour).

Discomfort Cost

Often in pavement management studies the issue of comfort and discomfort of users is not taken into account, because its quantification is difficult, as it is based on subjective judgment of the users. In literature there are various estimations of discomfort cost in relation with vehicle speed and pavement condition. The system presented in this article uses some data for discomfort cost (*11*).

Environment Cost

The cost to the environment consists of the pollution cost and the cost of extra noise as a result of pavement deterioration. The system includes only the pollution cost as a result of the extra fuel consumption to the atmosphere due to pavement deterioration. Pollution cost is calculated as follows:

$$C_{\text{pol}} = -\frac{L}{\text{Co} \times 100000}\,[0.234\ \text{TR} + 0.127\ (1 - \text{TR})]\ \ln\,(0.2\ \text{PSI}) \tag{35}$$

where C_{pol} is the pollution cost due to pavement deterioration for one vehicle (€/vehicle), TR is the truck ratio (%), and Co is the average fuel consumption of a typical vehicle (lt/km).

OPTIMIZATION MODEL SOLVING

The optimization model presented in the previous section is extremely complicated and for this reason it is desirable to use artificial intelligence methods to solve it. From the available methods of artificial intelligence, genetic algorithms are chosen for this system. One of the major reasons for using genetic algorithms to such optimization problems is their high efficiency. Genetic algorithms are optimization tools, capable of overcoming the extremely large number of possible solutions available, when other artificial intelligence methods do not manage it. They are robust search techniques formulated on the mechanics of natural selection and natural genetics. As such, they do not require differentiability, convexity or other auxiliary properties of the problem parameters. Genetic algorithms do not guarantee global optimum solutions, but if properly designed, they can often provide either optimum or near optimum solutions to the model.

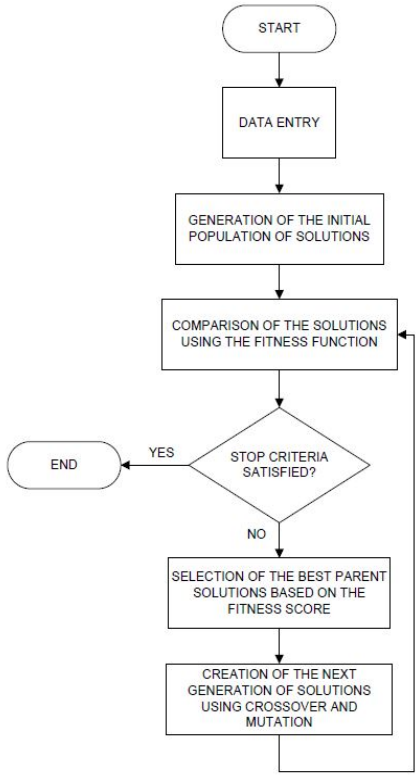


FIGURE 3 PAVEMAN flowchart.

Computer Program

The PMS of this article, PAVEMAN, is developed in C# and requires the NET Framework 4.0 platform. PAVEMAN can run under Windows XP and any later version.

The program structure is simple and is summarized in Figure 3. Each potential solution is a set of maintenance treatments, one treatment for each year of the analysis period for each road segment. The program stops when it reaches a number of generations set by the user and presents the solution that maximizes the objective function (Equation 1). The rate of crossover and mutation is controlled by the system user.

SYSTEM IMPLEMENTATION

A PAVEMAN session for five pavement segments and a 5-year time span is presented below. The environment of the system and the basic parameters used in this application are shown in Figure 4. The pavement segments applied for maintenance have similar characteristics but different age (Figure 5). Traffic flow is high in almost all pavement sections (except in section 4).

The alternative treatments chosen for this application are five: crack filling with aggregate–asphalt or other synthetic materials, local purge without squaring and laying of hot or cold asphalt preceded by adhesion, milling in layers and leveling with a 4- to 5-cm layer and then

antislip matting, antislip matting, and reconstruction. Finally there is always the option "do nothing."

The program is terminated in 10,000 generations and extracts the best solution in less than 2 min. The parameters *a* and *b* of the objective function are valued with 1, indicating that both components of the objective function are equally weighted for this application.

Tables 1 and 2 show two of the best solutions that the system produced. It is observed that the fifth section, which is virtually new (2 years old), does not need any maintenance since its condition is very good (PSI > 4). Particular emphasis is given in sections 1 and 4 which are old. Although segment 4 is older than segment 1, the latter needs the same attention because its traffic is high.

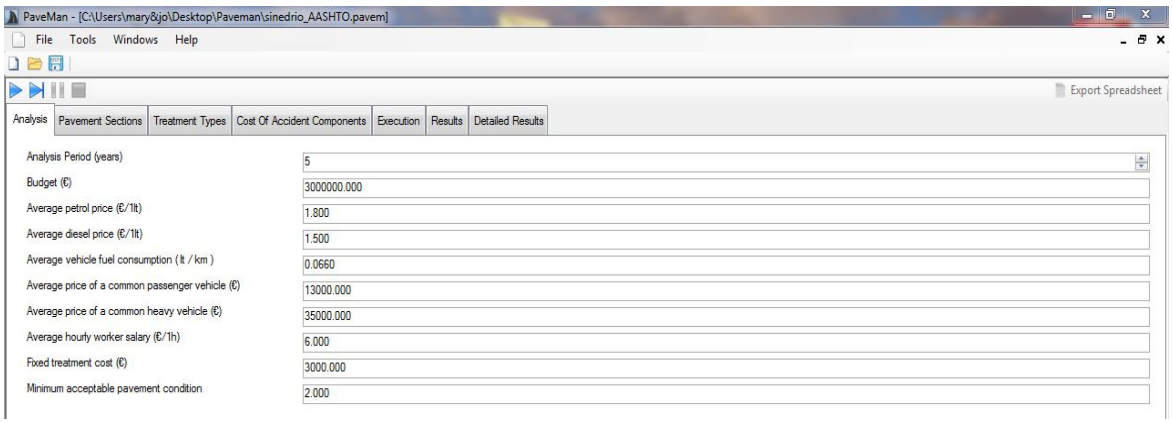
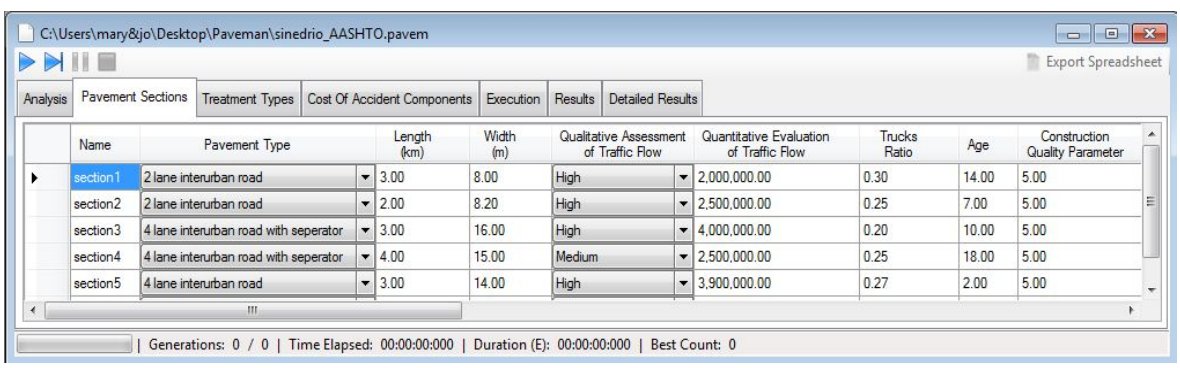


FIGURE 4 General parameter values of the application.



Name	Pavement Type	Length (km)	Width (m)	Qualitative Assessment of Traffic Flow	Quantitative Evaluation of Traffic Flow	Trucks Ratio	Age	Construction Quality Parameter
section1	2 lane interurban road	3.00	8.00	High	2,000,000.00	0.30	14.00	5.00
section2	2 lane interurban road	2.00	8.20	High	2,500,000.00	0.25	7.00	5.00
section3	4 lane interurban road with seperator	3.00	16.00	High	4,000,000.00	0.20	10.00	5.00
section4	4 lane interurban road with seperator	4.00	15.00	Medium	2,500,000.00	0.25	18.00	5.00
section5	4 lane interurban road	3.00	14.00	High	3,900,000.00	0.27	2.00	5.00

FIGURE 5 Pavement segment characteristics.

TABLE 1 A Solution of the System (not optimal)

Name	1	2	3	4	5	Agency Cost	Total Cost	PSI
section 1	Reconstruction					459000	1976801.52	3.6676
section 2			Local purge			70404	1152074.20	2.7393
section 3		Anti-slip matting				415800	3404663.78	2.4159
section 4		Miling in layers				901200	4411726.81	1.5534
section 5						0	1397848.11	4.0588
						1846404	12343114.43	2.8870

TABLE 2 An Optimal Solution of the System

Name	1	2	3	4	5	Agency Cost	Total Cost	PSI
section 1	Miling in layers					362280	2360831.79	2.5311
section 2						0	1222317.19	2.6091
section 3						0	5232656.33	1.7361
section 4	Miling in layers					901200	4465974.70	2.1637
section 5						0	1397848.1	4.0588
						1263480	14679628.14	2.6198

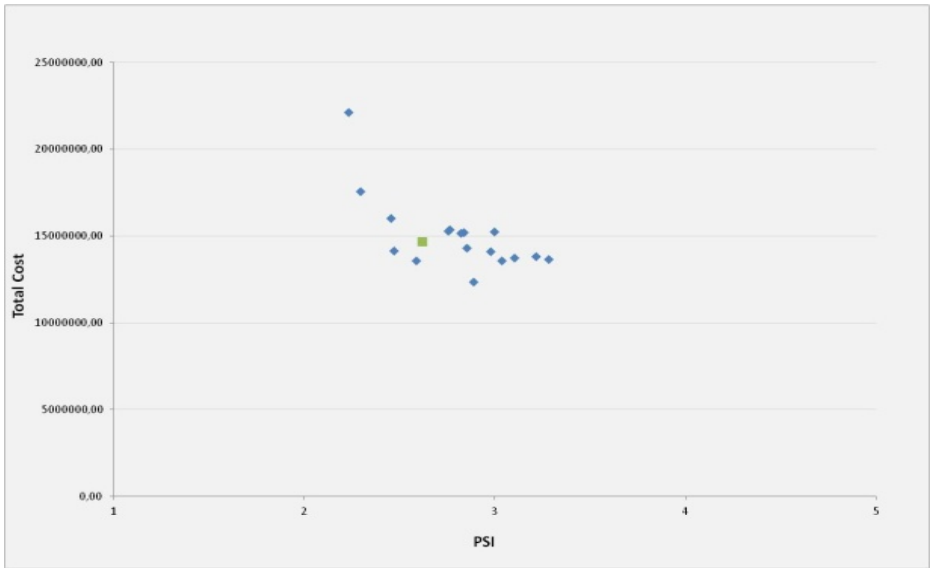


FIGURE 6 Total cost and pavement condition of the best solutions.

From the two solutions it is obvious that the second is better because it results in almost the same pavement condition as the first one, in quite lower agency cost, and in a relatively comparable generalized cost. The objective function confirms the above observations as it gets a value of 1.1979 for the second solution and 1.1951 for the first one. The program proposes the second solution, but it may be useful to compare the optimal result with other good solutions before making the final decision. In general, the repeated application of the genetic algorithm leads to discrete solutions that form a cloud of points in the decision parameter space. For instance, when comparing agency cost and pavement condition, the best solutions of the program form a cloud of points around a typical trade-off curve (Figure 6). In this formation, a Pareto-front of optimal solutions may be determined.

CONCLUSIONS

Nationally, pavements are deteriorating faster than they are being restored because maintenance funding has not been sufficient to take care of all needs. The pavement management system presented in this article aims to find optimal solutions for managing pavement segments, in other words to maintain road segments above a desired pavement condition threshold, minimizing the user cost and the cost to the environment without exceeding the maintenance budget.

The optimization is developed using a genetic algorithm. The system (PAVEMAN) is written in a new programming language that manages to solve large problems in a short period of time. An application case study consisting of five pavement sections with a 5-year analysis period and five available maintenance treatments is presented for which the system reaches the optimal solution in less than 2 min.

The most appealing aspect of the program is its effort to calculate a generalized cost parameter which includes the agency cost, the cost of users and the cost to the environment due to pavement deterioration. The data and individual models used in the system for calculating the generalized cost have been mostly derived from the literature. In future works, these data could be better evaluated and, if necessary, new measurements and experiments should be performed. Finally the optimization problem presented in this article could be solved with other artificial intelligence methods and results may be compared with the corresponding ones of PAVEMAN.

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Equipment Training and Implementation of New Technologies

EQUIPMENT TRAINING AND IMPLEMENTATION OF NEW TECHNOLOGIES

Equipment Mechanic Training and Certification

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A *Wall Street Journal* article from the weekend of November 26, 2011, cites the lack of trained individuals available for hire in the specialized skills arena. It was talking about well-paying jobs, with good benefits, that don't require a college degree. According to Craig Giffi, a vice chairman of the firm Deloitte Consulting, "there's a tremendous shortage of skilled workers." This statement is a result of a recent survey Deloitte did that found that 83% of manufacturers reported a moderate or severe shortage of production workers to hire. In the article they talked of the declining economy and organizations using a flatter organizational structure to reduce costs. This requires a work force that is able to produce at a higher level with less supervision. One of the points made was that their data showed that the skills gap doesn't exist in whole industries but in certain heavy-duty blue-collar ones. These jobs don't call for college degrees but require plenty of mechanical skills. Among these job skills are heavy vehicle mechanics, mechanics with electrical and electronic repair ability, and those with welding skills. These certainly are skills that are part of most job descriptions for our mechanic work force.

The article then talked about training and using training as part of a recruitment and retention strategy. So not only will training provide more cost-efficient repair and better availability of needed equipment resulting in less down time but it can help retain the people that you need to make this happen. When you do need to hire, a good training program can be used as a tool to recruit the quality replacement that you select for the position.

All of information just reinforces what we all understand: training is an investment. With budget dollars becoming tighter and tighter, you may ask is the value there or as a friend of mine often says, "Is the juice worth the squeeze?" I think we can agree that the above article says yes, the need is there. The benefits are in having a capable work force, retaining that work force, and recruiting replacements if you lose members of that work force. In other words, training is a multi-pronged investment.

The complexity of modern equipment is growing at an exponential rate. It is imperative that equipment repair technicians are continuously kept abreast of new technology affecting the machines that they are tasked with keeping available for their operators. There are an ever-increasing number of diagnostic tools being made available for them to use to find the fault more quickly and to get the repair right the first time. Knowing the diagnostic tools that are available, how to make them work for you most effectively, and being knowledgeable of evolving technology are never-ending tasks for the well-prepared fleet. With employer-provided training the following axiom applies, you provide it and you must also guide it. By guiding training, you have the ability to make the training reach those skills and knowledge pertinent to your equipment and needs.

Your technician's view will always be tilted towards the equipment they see in their shops every day. Training that has been customized to meet those specific needs rather than a generic training that may include your specific equipment works best, especially when it is conducted on your equipment. It is scheduled within a timeframe that you control and at your

facilities where the assets that your technicians have available every day will be used to accomplish the task at hand during hands-on training sessions.

To develop a good and usable training program, required or expected skill and knowledge levels must be determined. You must also determine the standards that you are willing to accept as recognition of the completion of the training task. There are skill sets (e.g., hydraulics mechanics and welders) that escalate with time and practice. Remember that these are your future masters within their field and as such their skills must be nurtured. This requires follow-on training and possibly more testing. Will you accept national certifications as your standard for satisfactory completion or do you need more stringent requirements met? Normally, national certifications will require periodic renewal and recertification. Often refresher training is required for certification renewal. This must then become a part of your overall training program. Do you try to promote from within? If so, there is additional training that may be necessary. All of this and much more must be worked through to make a training program effective and successful.

Any good program will begin with a needs assessment. While some individuals may feel that they have the understanding to make all of the necessary decisions to put a program in place, it is generally found that to effectively define training needs, it is best if more than one perspective be observed. To gain varied perspectives it is most valuable to use the advisory team concept to determine what training is actually needed. If a team is used, try to include experienced technicians from each level of your work force. Having their input provides focus on all levels of mechanical understanding at the technician level and the advanced technician level. The team should also include at least a small layer of shop supervisory input. This will ensure that the production control element remains visible. The team should be officially designated and contain representation from the entire working entity (recommend one member from each major physical area your equipment repair organization whether you call them districts, regions or areas). To make the advisory team most effective there must be a sponsor who can relate to the work that the technicians must actually perform on a daily basis. This is one of the most critical points. The sponsor will be the point of insertion with upper levels of the organization ensuring that what the team identifies and through discussions determine as needs, are then met.

In a full program, training to be provided must cover developmental courses, intermediate courses, and advanced courses. Most often, training needs are easiest to determine for the less capable technician. Just remember that the sharpest technician working on equipment also needs to continue to improve those skill sets that makes them the sharpest. Keeping this viewpoint is truly the means of ensuring a well-qualified and competent work force.

A look at the types of training and where this training might be found may be helpful:

- Developmental or core skills training—basic technician skills:
  - Use community college automotive training,
  - Use commercial school training,
  - Possibly use manufacturer training, and
  - Use in-house trainers (if you have truly qualified personnel).
- Intermediate skills training—more in-depth training to develop the technician to a level that reaches above basic levels while not yet reaching advanced skill and knowledge:
  - Use manufacturer training,
  - Use community college automotive training, and

  - Use commercial school training.
- Advanced skills training—training that places the technician in the top level of competency:
  - Use commercial school training,
  - Use manufacturer training,
  - Use community college automotive training, and
  - Use certifying entities training.
- Certification training: training designed to prepare technicians to compete for specific certifications. Normally will be "intermediate" or "advanced" training but can "core" type training. It is often developed from training that is already available but is pared to fit your specific needs.
  - Primarily commercial training,
  - Possibly community college automotive training,
  - Manufacturers will customize training for your equipment,
  - Certifying entities will help you find training that is designed to discuss and present their certifying criteria and make your work force able to meet those criteria for certification, and
  - Use in-house trainers (if you have truly qualified personnel).
- Designed training: training that fills your specific needs that is not otherwise available.
  - Commercial trainers,
  - Community college trainers,
  - Manufacturers trainers (possible although not often probable), and
  - Use in-house trainers (if you have truly qualified personnel).

Designed training is that which is developed for you and you alone. If you or your training needs team identifies a skill or knowledge need that you can't get filled through the common sources, you may find that it is best to design the training that you really need. There is some discussion later about using a partner to manage your program. If that choice is made, this is where your program partner can really pay dividends for you. When your managing partner understands your needs, they can find the proper people to develop a course containing the information that is truly needed with the knowledge and skill set incorporated in a manner that makes it most valuable to your work force. They are the point people guiding the project to completion while reporting progress to you.

National certification works in combination with your training program. It can provide the standards to verify that your training is meeting a level of completeness that is recognizable and certifiable. Another advantage is that most certifying entities provide for continuing education within the area of certification and most require recertification periodically to ensure that standards continue to be met. Many certification standards are updated on a regular basis to reflect the latest industry advancements.

Many may know of the American Public Works Association (APWA). This association has a certified public fleet professional examination that tests, among other items, human resource management. In this section of the examination content outline they inquire about employee training. The items listed are

1. Identify training needs of mechanic technicians, shop supervisors, drivers–operators, fleet managers, and new employees.
2. Conduct or authorize training (technical, safety, and best practices) for staff development and succession planning.
3. Encourage staff development through staff participation in professional organizations that promote the organizations' goals and objectives.
4. Establish annual benchmarks for each employee's skill levels and safety practices.

Certification is a natural follow on for the successful training program. Several mechanic technician certifications are available. Some of those are

- Automotive Service Excellence. Provides automotive and medium–heavy truck diagnostic and repair testing program and standards that are most recognized nationwide. They provide assurance that the technician recognizes various problems and the proper (or most probable) solutions to that problem, within any area of testing in which they certify.
- State vehicle safety inspector certification is a must for any state that has a state inspection program.
- State vehicle emissions inspector if your state has this requirement.
- International Fluid Power Society (IFPS) certification for fluid power mechanics or fluid power technicians. IFPS certification tests provide an objective, third-party assessment of an individual's skill level and are recognized industrywide. The certification offerings keep pace with changing fluid power and motion control technologies. IFPS strengthens and advances professional careers in the fluid power work force by requiring periodic recertification and providing educational opportunities for members. They provide access to a free electronic journal that allows technicians to remain current in this field.
- North American Transportation Management Institute has certifications for management personnel including certified supervisor of maintenance and equipment and certified director of maintenance and equipment. They also provide certified safety supervisor, certified safety director, and certified driver trainer.
- American Welding Society certifications are evidence that a welder has proven competency to a national standard for various welding processes (MIG, TIG, stick, structural, etc.). The standard chosen is dependent on the component and the material to be welded. Once a standard is selected the welder must prove proficiency based on material, thickness and positions of welding to be employed (flat, vertical, or overhead welding). To have technicians certified in the processes that are most useful to the work required in your shops ensures competency. This also requires documentation of the use of that process on a periodic basis.

Because this program is very specialized, day-to-day overall management of this training (and certification) requires a unique understanding of the needs that are being met along with dedication and commitment beyond what is normally available. Often in-house staff is unavailable or finding the right person, with the right background and qualifications, may be incompatible with their other staff duties. A truly effective training program is functional every day. It is a living, breathing, ever-changing program that must be managed. This may lead to the decision to outsource this portion of your program. The Virginia Department of Transportation (DOT) Equipment Repair Technician Training Program was the 2006 Winner of National Association of Fleet Administrators Larry Goill Memorial Quality Fleet Management Idea

Award. As a result of having insufficient staff, Virginia DOT used the request for proposal process to select a partner. They chose to use ManTech International–Systems and Advanced Technologies, Inc., to help with day-to-day management of their program. In their training program, the partnering program manager is responsible for finding, scrutinizing, and paying the vendors that provide training. This method saves time and staff resources by providing one itemized invoice per month to process rather than several vendors having to be scrutinized, controlled, and processed.

The Virginia DOT program found that another tool for helping to ensure success for the training program is having an equipment repair training coordinator assigned within each district (division, region, area, etc.). The coordinator must be familiar with the personnel, familiar with their equipment, and in a position to make decisions as to who will attend a training session when it is to be presented. This person is key to keeping the training program on track within each assigned area. They communicate with the ManTech program scheduler to determine candidates for any given training. The scheduler maintains a complete set of technical training records and from this information is able to provide the training coordinator with a list of candidates for any course that is going to be presented. The scheduler works with the vendors and the training coordinators to get the training to each area at a time that is acceptable for both. The coordinator also works with the supervisors to assign technicians to training. They ensure that the training facility is scheduled and that any necessary equipment or vehicle for the hands-on portion of the training is available. They coordinate with the instructor to set class times, suggest lunch schedules, and handle minor problems that may surface during the course of each training day. They fill the need for a point of contact between the training provider and the partner program manager. The scheduler and the coordinators must work together closely. They are a very integral part of the successful training program.

In summary, a good training program is a full process. It is recommended that the training needs be identified using a team. This team will help identify the standards that must be met with the training. Understand that management of the program must be knowledgeable, dedicated, and available to the program at all times. Coordination between work areas (districts, regions, etc.) and program management is the heart of the program, without which flowing technicians to the proper training becomes sporadic at best. Finding and procuring the proper training, at a proper level, using predetermined standards for each level and then coordinating the placement of the training at every facility requires a scheduler and a training coordinator that are in sync. The crowning point for that good program is national certification in any area of endeavor in which the technician is engaged. Certification will provide a strong benefit to your fleet by providing recognized standards that will lead to an improved work force and improved delivery of services to your fleet.

EQUIPMENT TRAINING AND IMPLEMENTATION OF NEW TECHNOLOGIES

Use of Automatic Vehicle Location Systems, Geographic Information Systems, and Global Positioning Systems to Increase Efficiencies and Decrease Cost in Maintenance Management

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Many businesses and government agencies are using automatic vehicle location with the global positioning system and geographic information systems in their work planning and execution. Use of these technologies can increase efficiency, reduce costs, and reduce the carbon footprint of any entity. This presentation will explain these systems and their costs, use, and benefits in the maintenance and operations field. When more than one of these systems is used together, efficiencies and cost savings increase to agencies. Several different systems will be demonstrated, including a "live" demonstration where a truck is tracked in real time via Internet log-in access, and work that is being accomplished is monitored. This system is currently in use with some departments of transportation, particularly for winter operations and in the maintenance of railroads. However, there is a much wider application for the use of these technologies that have become much more cost efficient in recent years.

Numerous government agencies and private businesses use geographic information systems (GIS) as well as automatic vehicle location (AVL) and the global positioning system (GPS) in the planning and execution of operations such as managing fleet, resources as well as personnel by collecting and storing the real time data. Post-processing and analysis of these data help them decision making, improvement of their process and thus creates lean business operations. While with the advancement of communication technologies allows the use of these technologies in myriad applications, this paper mainly focuses on how GIS, GPS, and AVL technologies are used in asset maintenance management to make this task cost-effective and efficient. The following sections in this report describe

- Overview of GIS,
- Overview of geospatial technologies that support GIS,
- GIS-based systems architecture,
- Survey of GIS-based applications in use,
- Issues, and
- Standardization of onboard data communications.

OVERVIEW OF GIS

GIS is an analysis tool that facilitates systems management and intelligent decision making through the use of spatial relationships among real world objects. It helps store, manage, analyze, manipulate and display spatially linked data, for an instance highway guard rail locations. Through relating asset information to physical locations, a GIS creates a "Smart Map" allowing users to perform advanced analysis on layered spatial information. This technology is used throughout many transportation organizations [departments of transportation (DOTs), metropolitan planning organizations, and FHWA, etc.] to prioritize strategic goals and assist in the planning and execution of key project elements, such as highway winter maintenance.

OVERVIEW OF GEOSPATIAL TECHNOLOGIES THAT SUPPORT GIS

The following geospatial technologies warrant descriptions due to their widespread use as the enablers of the GIS technology in various GIS-based applications.

Global Positioning System

GPS is a satellite-based positioning system that provides location and time information in all weather, anywhere on or near the Earth. GPS must have an unobstructed line of sight to four or more GPS satellites to calculate its position precisely. The U.S. Department of Defense operates the GPS system. Sometimes multipath interference due to the signal bouncing off by nearby objects reduces GPS's ability to accurately determine the position.

GPS accuracy was not so precise before the year 2000. At that time the accuracy was limited to ±100 m. The U.S. military introduced random timing error to limit the accuracy to deter any adversary from doing any harmful activities to United States. Since the year 2003 the accuracy of GPS determination has increased dramatically (±10 m) depending on the number of reference satellites.

Even this level of accuracy is not very useful in highway asset management activities. GPS accuracy can be up to ±1 m by applying differential GPS (DGPS) correction to the calculated GPS location. DGPS is based on at least four satellites and real-time communication to any known local reference point. GPS location corrected with a DGPS can be accurate up to ±2 mm depending on the type of reference points used, the amount of post processing, duration of observation, and the location of satellites.

Since it is open to public use, many civilian applications have been using one or more of GPS's three basic components: absolute location, relative movement, and time transfer. Several DOTs use GPS's absolute location component in their fleet tracking system, utilizing GPS to identify, locate, and maintain up-to-the-minute accurate locations for one or more fleet vehicles.

Automatic Vehicle Location

AVL provides real-time location information for any mobile assets upon which it is installed. The mobile assets could be snowplows, dump trucks, emergency vehicles, etc. AVL collects the mobile asset's current location (from integrated or interfaced GPS) and can also collect data from other sensors installed onboard. The collected data could either be stored or sent to a

centralized location for data analysis. Sensors that can be used with AVL include simple toggle switches for the cab door (open or closed) or plow blade position (up or down) to more sophisticated sensors that capture the vehicle speed, the snow pressure on the plow blade, or the rate of salt dispersion. Data collected from AVL in field is sent to a centralized location and can be analyzed and overlaid on a GIS layer. The GIS layer data can be represented on a map and monitor the progress of the task in real-time. Also the analysis of the AVL data helps asset managers in determining whether or not to adjust work plans which then can be transmitted to the vehicle or operator. For an example, road temperature data from a roadway weather information systems and meteorological forecasts from National Oceanic and Atmospheric Administration can be used to instruct the salt spreader to reduce the flow rate on a specific stretch of highway. Monitoring the updated spray rate on this stretch of the road from the central location helps managing the budget of the job.

GIS-BASED SYSTEM'S PHYSICAL ARCHITECTURE

Figure 1 depicts the communication interface between the AVL–GPS (modem GPS) on a maintenance vehicle and the GIS-based host end application. The figure shows the basic building blocks of an AVL–GPS data collection system. The modem GPS unit collects the data and sends it to the server over the wireless network. The wireless network can be in many forms but in general it functions as the network of radio transmission and provides a seamless interface between the AVL on the vehicle and the web-based services on the host computer. This system provides information anywhere with an access to the network. Data from existing legacy systems (fuel management, timecard, and work order or repair work order system) and from the AVL–GPS system can be integrated to maximize the use of the AVL–GPS data.

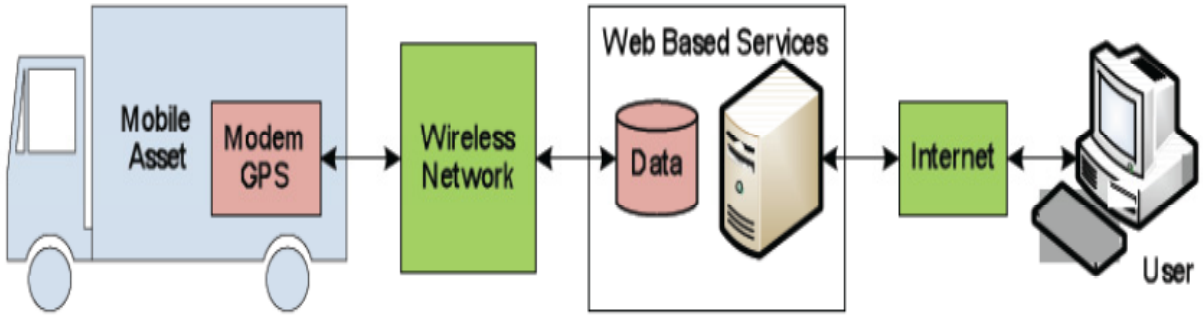

FIGURE 1 Generalized GIS-based system architecture (Source: Clear Roads Development of Interface Specifications for Mobile Data Platforms on DOT Vehicles in Cooperation with Clear Roads, Concept of Operations for Specification, April 8, 2010.)

GIS SOLUTIONS FOR HIGHWAY AND ROADWAY MANAGEMENT

Relations between objects and events of all transportation challenges are located in different spatial positions and they are all geographical in nature to different degrees. The more logical way to store and relate information is through spatially consistent referencing system such as GIS since the data required has always spatial nature in it. Furthermore, GIS provides a common platform in enhancing the several transportation related issues. For this reason, GIS is a natural choice for manipulation and analysis of transportation infrastructure information.

A GIS-based centralized information system provides an information technology framework for maintaining and deploying data and applications through every aspect of the transportation infrastructure life cycle. The following sections provide a brief description of how GIS-based system can be used in different aspects of the transportation infrastructure life cycle and then the main topic of this paper is described in detail in the next section (Figure 2).

Planning

GIS provides a way of spatially identifying deficiencies and determining optimal solutions on transportation projects. Compliance with the National Environment Policy Act for maintaining quality of life and environment sustainability while providing adequate capacity to meet the demand on public infrastructure is a major challenge for transportation planner. GIS provides rich analytic and visual tools which helps meet the challenge. The information from GIS

FIGURE 2 Enterprise GIS in transportation infrastructure life cycle. (Source: GIS Solutions for Highway and Roadway Management.)

framework can be used for travel demand forecasting and capital planning modeling and thus assists in strategic decision making. The impact of various transportation alternatives on the environment can be assessed by various GIS-based applications that perform environmental evaluation.

Design

Most design tools such as computer-aided design can be integrated into GIS which will provide greater analytic and cost-estimation capabilities to a transportation infrastructure design process.

Survey

Manage, store, and display GPS data and survey measurements more effectively.

Construction

Interfacing project and financial management software with GIS provide better management capability for project engineers of transportation infrastructure projects. GIS provides a single point of entry for all construction-related documents.

GIS provides all information related to a transportation project to project staff through a browser interface. Project information that can be integrated in GIS includes survey data, soils, and geotechnical studies, planning, environmental studies, engineering drawings, and project maps. The availability of all this information at one interface reduces time spent searching for needed information and increases efficiency.

Operations

GIS enhances operational performance when integrated into the operational business process. Real-time video and data from traffic sensors can be integrated to a GIS system. In this way GIS is a central part of a traffic management system. Traffic managers can visually monitor the bottlenecks and related information in real time and can provide efficient options to reduce the impact. Moreover, looking at the video, traffic operations engineer can visually confirm a traffic incident at a highway location covered under the view of the camera and respond quickly to clear the incident to normalize the traffic.

Maintenance

Maintenance budgets can be managed efficiently by integrating asset inventory with inspection history and work order management in a GIS-based central system.

Use of GIS in Highway Asset Management

With the increasing number of aging highway infrastructure and the declining maintenance budgets state DOT agencies are facing unprecedented challenges to do more with less available resources. Many states' DOTs are trying to find cost-effective and innovative solutions to the dilemma of the gap between available funds and funds required to maintain the highway at an

acceptable level of performance with ever-increasing demands on the state highway system. The decision-making process is getting increasingly knowledge intensive and requires efficient access to a wide range of accurate, detailed, and up-to-date asset information. Efficient operations and cost-effective decision making at all levels of asset management require efficient management of asset information. The quality of the decision-making process can be improved with the spatial component added by these systems.

GIS is an ideal tool to implement a more intuitive and efficient methods to manage, query, explore, visualize, and analyze the highway and railway asset data in a spatial context. Also it is possible to access the asset data and manage and integrate highway spatial data with non-spatial data. Spatial analysis and visualization provided by GIS better support the planning and decision-making processes.

With recent advances in GIS and other geospatial technologies (AVL, GPS) in general, as well as the low cost GIS software's availability, many DOTs are seriously considering integrating these technologies into their asset management processes.

In an asset management application domain, GIS with AVL and GPS facilitates asset data collection, data processing, and data display. Construction, operational, and maintenance budget can be centrally managed by integrating asset mapping with project management and budgeting tools.

Efficient, prudent, and logical distribution of scarce maintenance budgets can be allocated among competing objectives with the help of an asset management system. Loading the asset management system on mobile devices, field personnel can take the detailed GIS asset mapping into the field and quickly locate the relevant assets and perform inspection tasks. Any deficiencies identified will generate a new work order for maintenance and repair.

Many highway agencies gain productivity and efficiency by adopting a GIS based highway asset management system. Asset management systems provide more efficient scheduling of maintenance activities and tracking of work, personnel, equipment and material usage. These functionalities of GIS help managers monitor, understand, and report maintenance activities.

GIS, GPS, and AVL Technologies in Use at State DOTs

A survey on GPS–AVL use in DOTs has been performed by Erle Potter from Virginia DOT in 2011 to know how many state DOTs are using this technology. Also included in the survey response was the information about the hardware used, type of applications used, types of data that are collected now, types of data that DOTs are interested to get in future, who are users of collected data and issues related to installation, compatibility in sensors, data flow, and what kind of applications the state DOTs are eager to have in future. The result of the survey was presented by Marie Venner from Venner Consulting in the AASHTO Maintenance Meeting on July 19, 2011 at Louisville, Kentucky. The presentation includes the following information about the survey.

GPS–AVL Applications

From the response it is found that 23 states are using GPS–AVL system for their maintenance activities (Table 1).

TABLE 1 Types of GIS–GPS–AVL Applications in Use

Application Name	States That Are Using the Application
Maintenance decision support system (MDSS)	Colorado, Idaho, Kansas, Wyoming, Nebraska
Interfleet	Missouri, Ohio, Kentucky
In-house development underway	Iowa, Washington
Radio frequency identification	Alaska
Application-supporting MDSS	New York
Fleet tracking	Illinois
AVL–Acadian Mobile Monitoring	Louisiana
Telenav	Maryland
AmeriTrak AT500 telematics system	Minnesota
WexSmart	Montana
Vision Link, JDLink	Kentucky
Skypatrol	North Carolina
Location technologies	North Dakota
Custom software by Intelligent Devices	Nebraska
Networkfleet	New Mexico
Geospatial Analysis of Threats and Incident Reports	Pennsylvania
LOCATE/IM	Tennessee

Data Collected from the AVL–GPS System

The data that comes from the AVL–GPS systems used by the states are not same for every state. Table 2 shows the kind of data that are collected, data usage, and the names of the sates.

Some DOTs want the following controller area network (CAN) data from vehicle with the other GPS–AVL data to manage the maintenance resources better:

- Atmospheric pressure,
- Wiper status,
- Headlight status,
- Sun sensor,
- Accelerometer,
- Impact sensor,
- Steering angle,
- Anti-lock braking system status,
- Vehicle error codes,
- Idle time, and
- Streaming video.

Future Hardware and Applications

The DOTs that use GIS–AVL–GPS system and responded in the survey also mentioned the types of application that they are planning to acquire in future. DOTs are planning to adopt applications that can provide management level data by integrating GPS and AVL data with data

TABLE 2 Data Types and Usage from GPS–AVL System

Usage of GPS–AVL collected Data	State(s)
Data: Speed, materials types and quantities, application rates, and temperatures. *Usage:* Operational–snow fighting efficiencies.	Delaware, Kansas, Kentucky, Maryland, Minnesota, North Dakota, New York, Washington
Data: Real-time vehicle location *Usage:* Tracking vehicle location and route improvements–efficiencies	Illinois, Kansas, Kentucky, New Mexico, New York, Wyoming
Data: Real-time vehicle location Usage: Tracking vehicle in extremely remote areas	North Carolina, New Mexico
Data: Road conditions *Usage:* Near real-time road conditions data over the states	Washington
Data: Locations *Usage:* Locations of incarcerated crews, history–daily achievements of sweeping crews.	Missouri
Data: Locations, track and trace, engine parameter data *Usage*: Contractor vehicle usage while "on the clock"	Virginia
Data: Photos, rate of material application *Usage:* Tracking the material use	Nebraska
Data: Locations and vehicle bed load weight	Alaska, Kentucky
Usage: Mapped areas of noxious weed control. Forecasts to make informed decisions regarding striping, chip sealing, paving, and fog coating	Colorado
Data: Location *Usage*: Emergency patrol and snow and ice truck tracking	Illinois
Usage: MDSS	Kansas
Usage: Motorist Assistance Patrol Unit applications	Louisiana

from other sources such as weather sensors, vehicle's CAN and video monitoring. The responses from the survey indicate the following future application:

- Applications that can translate many data points into management-level data for asset management system, yet maintain sufficient data granularity for certain aspects of the operation.
- Applications that can integrate mobile weather data using ambient temperature sensors and infrared sensors in places where forecasting is very sparse.
- Application capable of incorporating relative humidity, precipitation and road friction data from sensors on snow plow truck with GPS–AVL data that are able to suggest the estimated rate of material application in real time.
- Hardware to collect data from vehicle's CAN BUS.
- Applications to display streaming video from plow trucks in real-time during operation.

CONCLUSION

DOTs are experiencing a huge challenge to maintain their highway system at an acceptable level of service with the decreasing amount of available maintenance budget. A crucial strategy to meet the challenge is to enhance the efficiency and effectiveness of asset management process. Using of IT, in general, and of GIS with GPS and AVL, in particular will help in implement the strategy. This paper describes the available and future GIS–GPS–AVL applications that can be used in asset management projects. The survey of current status of using the GPS–AVL system in use by various DOTs revealed that further research needs to be completed through AASHTO and NCHRP to find solutions for issues that DOTs are facing today in these technologies. The identified issues are lack of standard data requirement among various DOTs, absence of standard protocols that will enable different devices interoperable, difficulty in installation and lack of sharing the collected data between GIS systems of neighboring states etc. However, Significant progress in standardizing transportation on-board data communications and vehicle health monitoring system using FHWA best practices documents, National Transportation Communications for ITS Protocol (NTCIP) and Society of Automotive Engineers (SAE) standards has been made.

GIS–GPS–AVL based asset management system provides more than the classic dots on maps or location information. An asset management system provides DOTs to best manage their field resources in time and space adapt to real-time operational needs and provide real-time information about where their mobile asset maintenance vehicles are now, where they have been, where they should be and how they are doing in respect of their assigned schedules. For an agency to better manage its asset maintenance task, adopting the GIS–GPS–AVL based system is the logical next step. Technology is available, all it is matter, to think of using all available assets both in office and in field.

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EQUIPMENT TRAINING AND IMPLEMENTATION OF NEW TECHNOLOGIES

Connecting Automatic Vehicle Location, Global Positioning System, Maintenance Decision Support System, and Intelligent Transportation Systems to Improve Traveler and Highway Maintainer (Snowplow Operator) Safety

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During the past decade, significant improvements have been made to decision support systems for maintenance personnel, promoting more effective and efficient responses to winter weather. Decision support systems, available in various forms for decades in the maintenance and operations of highways, often are provided as a discreet set of predefined responses for given road weather events driven by rules in a standard maintenance practices document. New refinements to decision support systems include ingest of near real-time vehicle data from mobile platforms, including plow sensors and ground speed control spreader information. These refinements also include improved algorithms that use current weather and treatment information to formulate more effective snow and ice removal treatment recommendations. Even the awareness of road weather conditions itself serves as a decision support mechanism. While recent maintenance decision support systems (MDSSs) have brought together the maintenance and surface weather communities, one important group, the intelligent transportation system (ITS) community, has been left out. The authors of this paper are currently working on a project that ties the three groups together with the ultimate goal of improved safety for the traveling public and the highway workers that maintain the roadways. Iteris, Inc., along with its project partners, Meridian Environmental Technology, Inc., are currently under contract with the Minnesota Department of Transportation (DOT) to develop a new highway traveler warning system that will integrate MDSS automatic vehicle location (AVL) data, weather-provided services, and ITS technologies. One of the project's goals is to provide highway travelers with a caution–warning message in an automated fashion as they approach a slow-moving snowplow. MDSS AVL data will be used to communicate warning messages that are displayed on dynamic message signs as the truck passes the sign. The message will be removed from the current sign once the truck has passed the next DMS, at which time the warning message will be displayed on the next sign. Information collected from the maintenance vehicle and weather service provider will be used to determine the correct messaging for the sign, i.e., "Snowplow Ahead" for winter snow removal activities and "Maintenance Vehicle Ahead" for summer activities. An operational test of the system is scheduled for deployment by November 2012 and will be evaluated by SEH, Inc. This paper will address the challenges and opportunities that are presented when maintenance and ITS technologies are combined to provide improved traveler information. New uses of existing technologies within the maintenance, ITS, and road weather service provider areas will be investigated for use in improving traveler information and highway safety. Challenges of the current project with Minnesota DOT will also be discussed. Finally, outcomes resulting from the deployment of the project will be presented.

Performance Measures, Decision Support, and Risk Management in Highway Maintenance

PERFORMANCE MEASURES, DECISION SUPPORT, AND
RISK MANAGEMENT IN HIGHWAY MAINTENANCE

Performance-Based Maintenance and Operations Management

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Interest in performance-based maintenance and operations management is driven by both a growing recognition of the importance of highway maintenance and operations (M&O) and the increased focus on performance management. While past studies have focused on the elements that contribute to a performance-based highway M&O approach, comparatively little work has been reported on how managers actually use performance-based methods in their business decision processes. The application of performance-based management to highway M&O is the subject of this paper, focusing on state DOT usage. The study was conducted through the NCHRP Highway Synthesis Program, with data developed through responses to a survey and development of four case examples involving state departments of transportation (DOTs) with new or mature performance-based M&O programs. Based upon the nationwide survey in which 80% of state DOTs participated, three-quarters of responding agencies reported using some type of performance-based method for highway M&O management. Survey results also showed that while there is considerable variability in the details of individual performance-management programs, agencies agree on more fundamental matters, e.g., the management tasks to which performance-based methods can be applied and factors important to setting goals and targets for performance assessment. Four case examples reinforced and built upon the findings of the survey to illustrate how individual performance-based elements come together and are applied by agencies to different management needs and tasks. These cases illustrated the versatility of performance-based methods in managing the highway M&O program and in addressing other policy and management issues that affect highway maintenance and operations.

Interest in performance-based maintenance and operations management is driven by both a growing recognition of the importance of highway maintenance and operations (M&O), and the increased focus on performance management. While past studies have focused on the elements or components that make up a performance-based M&O approach, e.g., condition ratings, levels of service (LOS), performance measures, threshold values—comparatively little work has been reported on how managers actually use performance-based methods in understanding maintenance policy and investment options, reaching decisions, and accounting for the consequences of those decisions. The application of performance-based management to highway M&O is the subject of this paper. While the focus is on state DOT usage, other agencies can also benefit from this knowledge of current practice.

This paper for the most part draws on the recently completed NCHRP Synthesis Project 42-06, Performance-Based Highway Maintenance and Operations Management. Results of this study are documented in NCHRP *Synthesis of Highway Practice 426* (*1*). Results discussed or summarized in this paper encompass the findings of the Project 42-06 literature review, survey of state DOTs, and case examples.

PERFORMANCE MANAGEMENT AND MAINTENANCE QUALITY ASSURANCE

Performance-based M&O management has been influenced throughout the past decade by Maintenance Quality Assurance concepts (MQA), as promoted by *NCHRP Report 422* (*2*). While MQA has provided an overarching framework for a number of M&O management implementations by state DOTs, this paper adopts the concepts, methods, and nomenclature of performance-based management (also referred to as performance management). This shift is an evolutionary one, not a departure from the ideas and methods of MQA. The following sections explain the rationale and advantages of moving to a performance-based framework.

Research in Maintenance Quality Assurance

Much of the research related to MQA to date has focused on the elements and tools needed: e.g., the set of performance measures that best represents maintained features or maintenance services, and the analytic relationships needed to make MQA work: e.g., the linkage between facility or feature performance and the cost of maintaining it in an operable state. Less attention has been paid to how managers actually use MQA concepts, methods, and tools in their day-to-day business processes and decisions. Furthermore, since the publication of *NCHRP Report 422*, the somewhat broader and more widely applicable framework provided by performance-based management has emerged to begin gradually superseding the concept of MQA as an organizing principle, as will be explained below. Both MQA and performance-based approaches allow for elements and procedures that have become familiar to highway M&O managers, e.g., performance measures, LOS, the use of field data collection to quantify measures and service levels, LOS targets, and so forth. For purposes of this paper, the terminology of performance-based management will be used as the primary nomenclature; MQA will be used only when referring to the historical development of highway maintenance management practice, or to state DOT practices that have been specifically labeled as MQA.

Performance-Based Management

The recommendations in *NCHRP Report 422* anticipated many features and procedures that are still in use or are now being implemented in selected performance-based methods reviewed in this study. However, performance-based management is a more current usage that incorporates the elements and procedures envisioned in MQA above, but recognizes additional capabilities as well (listed below). A performance-based approach provides a more recognizable fit to the considerable work now underway at the federal, national, and state levels regarding performance measurement and accountability. A number of reports and guidelines involving applications of performance-based approaches to highway activities and decision-making have been produced by AASHTO, NCHRP, the General Accounting Office, the USDOT/FHWA and other organizations. A performance-based approach anticipates provisions in the future federal reauthorization of the surface transportation act: As of Summer 2011, both House and Senate proposals for this bill included mention of accountability for performance (*3*, *4*). Beyond consistency with these other developments, a performance-based approach to highway maintenance and operations gives more explicit recognition and emphasis to the following capabilities:

- Management accountability reporting. Accountability reporting is a key part of governmental applications of performance-based management. Accountability reports typically involve a comparison of proposed target service levels to actual LOS values attained. They indicate not only the resulting maintained condition of the highway as compared to forecasts, but also a measure of the quality of stewardship exercised by the state DOT in the management of its M&O program and its results.
- Customer satisfaction. The MQA process explicitly considered customer input in both the design and the implementation phases. Subsequent research has observed that since 2000, the measurement of customer satisfaction had evolved independently of maintenance quality assurance, to the point that agencies began to consider customer satisfaction as "related to but separate from their MQA programs" (*5*, p.33). Performance-based concepts can help restore the importance of customer outreach as part of the consideration of factors used to set M&O priorities, threshold values and grading curves for LOS definition.
- Comprehensive processes for updating and renewing performance-based components. Current performance-based approaches treat updates and renewals comprehensively, encompassing reviews of unit costs, LOS targets, M&O priorities, condition and performance measures, and thresholds/ ranges of values defining LOS grading curves, among other items.
- Expanded approaches for incorporating maintenance priority. The MQA guidelines envisioned maintenance priority as a weighted-value calculation. While some performance-based approaches continue to use this method, others apply different methods: e.g., the contribution category matrix used by Wisconsin DOT, with resulting adjustments in LOS grading curves to reflect priority (*1*).
- Inclusion of mobility and operations-related features and activities. MQA development included many features and activities with performance measures expressed in terms of physical asset condition. Policy objectives of M&O were described in terms of safety, preservation of investment, user comfort and convenience, and aesthetics. Performance-based M&O management today increasingly recognizes the importance of operations-type activities and of traffic mobility as a fifth core M&O objective. The MQA implementation plan recognized other potential M&O policy objectives such as environmental protection. Performance measurement continues this thinking.
- More comprehensive accounting of highway performance and cost. Whereas the MQA guidance focused solely on features and activities within the scope of the M&O program, some M&O organizational units are moving to a more broad-based communication of performance-based results. These approaches incorporate data on activities and services that are not performed by an agency's highway M&O unit.

DEFINITIONS

The following definitions are used in this paper within the context of performance-based highway M&O management:

- Performance measures: indicators of road-related physical or aesthetic condition, quality of maintenance and operations services provided, or operational behavior of highway traffic, from an agency or a customer perspective.

- LOS: translations of performance-measure information to a defined scale that indicates degree of acceptability or degree to which current performance meets expectations. While performance measures are defined by a highway agency, they are often intended to reflect customer needs and expectations. LOS may be expressed on different types of scales—e.g., numerical scores, letter grades, or qualitative descriptions such as high–moderate–low—but in each case the method of arriving at a particular LOS is clearly defined and replicable by different individuals. Also referred to as service levels or by agency-specific identifiers [e.g., Florida DOT's Maintenance Rating Program (MRP) ratings].
- Performance-based management: techniques based upon performance measures or levels of service that can be used to describe current highway system status, define goals and targets for accomplishment, evaluate strategic and tactical options to attain goals and targets, track progress toward goals and targets, relate both identified needs and actual work performed to cost, and report on the results or outcomes of these tasks.
- Maintenance and operations (M&O): actions devoted to keeping a highway in serviceable condition, enabling it to perform as intended. Since agencies treat the relationship between maintenance versus operations differently, hard-and-fast distinctions between the two will be avoided. As general guidance for this paper, "maintenance" refers to the preservation and repair aspects of M&O, while "operations" refers to actions promoting safe, predictable traffic movement. "Maintenance and operations" or "M&O" will be used to emphasize the total program or the comprehensive nature of the M&O function. In general descriptions with no qualifications, "maintenance" may be used with the understanding that the term encompasses operations as well.
- Maintenance Quality Assurance (MQA): planned and systematic actions needed to provide adequate confidence that highway facilities meet specified requirements. Such requirements are usually defined by the highway agency but are intended to reflect the needs and expectations of the [road] user (*2*).

CURRENT STATE DOT PRACTICE

Overview

The description of current state DOT practice sought to address the following items:

- The extent to which state DOTs use performance measures or levels of service, with examples of how these components are incorporated into their management practices.
- Examples of performance measures that underlie levels of service for selected M&O activities.
- Processes and methods of quantifying threshold values governing pass-fail evaluations, and values defining individual service-level boundaries.
- The consequences of not meeting (or exceeding) targeted M&O service levels at state and district–division levels.
- Applications of levels of service to M&O by contractors as well as by agency forces.
- How performance measures or levels of service are used to establish M&O priorities and to manage performance in the short term as well as the longer term.

- Methods of communicating M&O performance targets and results internally, to legislators, other stakeholders, and the public.

Investigations of these items were pursued in Synthesis Project 42-06 through a literature review, a survey of U.S. state DOTs, and documentation of four case examples that looked in greater detail at specific applications of performance-based management to highway M&O. This paper presents selected examples and highlights of this research, focusing on a subset of survey findings and capsule summaries of the four case examples. Readers interested in additional detail should consult *NCHRP Synthesis 426* (*1*).

Survey of State DOTs

What the Survey Represented

Much of the past research in this field has centered on the elements of performance-based management – e.g., measurement of condition, formulation of performance measures, different approaches to levels of service, definitions of targets and thresholds, and the like—and their comparison among North American transportation agencies. The focus has been, as it were, on the "tools" in the performance-based toolbox and how they are "manufactured." This study looks instead at how the "skilled craftsmen" within highway maintenance and operations organizations apply these "tools." This study recognized that "tools" used by state DOTs differ in their "materials and manufacture" – varying field data collection procedures and conventions, different constructions of performance measures, pass–fail versus graded measures of LOS, different thresholds and target values, and so forth. The study acknowledges these differences, but otherwise does not address them in any detail. Rather, the purpose of this study is to understand how these "tools" are applied to build, operate, and sustain a successful performance-based M&O program to the benefit and satisfaction of both the agency and the customer. The design of the NCHRP survey questionnaire was based on this objective.

Survey Response

The survey conducted for this study yielded 41 responses. Of these, 31 state DOTs reported using a performance-based approach for managing maintenance and operations; 10 reported not using such an approach. During the design of the survey questionnaire, a pre-test involving state DOT representatives on the Topic Panel had indicated that performance management usage might actually encompass a number of variants on performance-based approaches and different stages of development. These multiple possibilities were built into the survey questionnaire. For those agencies reporting that they did not use a performance-based approach for managing maintenance and operations, the questionnaire asked about the method that was being used and reasons for not currently adopting performance management.

Categories of Management Approaches

For those agencies that reported use of a performance-based highway M&O approach, their current status was described using one of six categories, with the number of responding agencies in each category also given below and illustrated in Figure 1:

- Category 1: Primarily Condition and Performance Data Tracking. The five agencies in this category collect performance-based information regarding M&O assets or actions. This information is used primarily to track conditions and performance and to inform various management decisions. However, procedures and other performance-based elements (such as performance targets) are lacking to be able to provide a more comprehensive and formalized management treatment of problems across a broad M&O program.
- Category 2: Strategic or Generalized Program Performance Measures. The three agencies in this category subscribe to performance management at a broad level. Performance measures are strategic, applying to a range of agency programs and investments. For example, pavement and bridge condition may be expressed by a generalized pavement-surface condition and bridge health index; safety, by frequency of fatal and serious-injury collisions; and mobility, by cumulative hours of passenger and freight delay. While these performance measures may reflect the consequences of certain M&O actions and services, they are also affected by capital projects (e.g., for asset rehabilitation and operational improvements) as well as initiatives and investments by other transportation agencies and programs (e.g., for law enforcement and driver education).
- Category 3: Performance-Based Approach Just Beginning. The three agencies in this category are just beginning their performance-based program design and development. It could not be assumed that these agencies would yet have developed the information needed to complete the substance of the questionnaire. Accordingly, these respondents were asked instead for a brief description of their proposed effort.
- Categories 4 through 6. The 20 agencies in these three categories have an in-service performance-based program addressing a range of assets, activities, and services. These three categories are examined with the same set of questions in the survey, and receive the most extensive, detailed coverage. They are, however, distinct in the following ways:
  - Category 4: Maintenance and Operations Performance Measures (6 agencies) refers to performance measures as opposed to levels of service as the basis of their approach.
  - Categories 5 and 6: Preliminary or Mature Maintenance and Operations Levels of Service (6 and 8 agencies, respectively) have levels of service as the performance element of their approach. Category 5 describes those agencies whose levels of service are preliminary and may be revised in the near future. Category 6 describes those agencies with a mature LOS program, implying more stable elements and values and potentially a greater tendency to explore more far-reaching research, more refined or sophisticated management capabilities, and a wider range of applications.

The categories of responding agencies that use performance-based approaches could also be aggregated further within groups. Groups are helpful because, even with more than 80% of state DOTs responding to the survey, results are diluted when distributed among the several possibilities in Figure 1. Interpreting the results in groups helps to provide a higher-level perspective. As an example, there is no significant concentration of questionnaire responses in any single category in Figure 1. However, when categories 4 through 6 are viewed collectively, one perceives a critical mass of support for, and use of, a performance-based approach. This group represents agencies that already have a program of performance measures or levels of service oriented specifically toward maintenance and operations. One's perspective on this group

is strengthened by adding those agencies that are just beginning a performance-based process (Category 3 in Figure 1).

Responses to Selected Questions

The survey questionnaire included more than a dozen questions addressing the topics outlined in the Overview to this section. Excerpts of responses to three survey questions are provided below as examples. The examples ask agencies about their M&O management tasks that are addressed by a performance-based approach, about goals and targets (if any) that are set for the M&O program, and about innovative approaches to operations-type activities. The complete survey results are included in *NCHRP Synthesis 426* (*1*).

Management Tasks Supported by Performance-Based Approaches From the list of management tasks in Table 1, most agencies selected from the first six as their focus for applying performance-based techniques.

Additional comments by respondents that are related to management tasks included the following:

- One agency observed that while it has defined M&O performance measures and levels of service, they are not widely integrated into management tasks because supporting data are not sufficiently timely for decision-making.
- A second agency is looking to use performance-based tools to prioritize M&O work, but work on this is in its infancy. Funding challenges (with needs far greater than the resources available) limit the DOT's ability to allocate resources based entirely on MQA results.
- In separate discussions with two other states, they remarked that previously developed performance-based capabilities were not used anymore. In one case this was due to the difficulty of having a LOS-cost relationship work meaningfully given the uncertainties in funding. In the second case this was due to an update in maintenance management software,

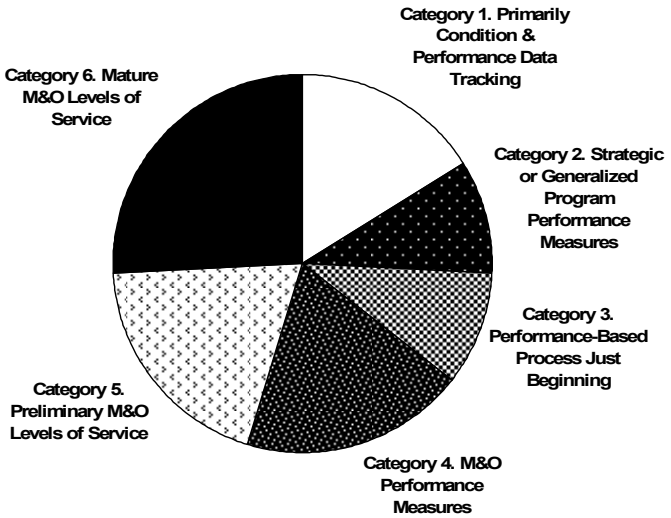

FIGURE 1 Categories of performance-based development among reporting agencies.

TABLE 1 Survey Results: Management Tasks Supported by Performance-Based Methods

Tasks Supported by Performance-Based Methods as Reported by Agencies	Number of Responses
Tracking of condition, performance, or quality of M&O assets–activities	18
Development of needs-based management estimates	13
Maintenance and operations prioritization	15
Budget development and justification	15
Resource allocation among districts/divisions/regions	11
Analytic relationships between LOS and cost	8
Anticipation of future management requirements in reauthorization legislation	1
Innovative communications techniques	2
Other tasks	2
No response	0

Note: Respondents could select more than one choice above.

where the new product would not be able to support the computational procedures that had previously been used to estimate a particular LOS-versus-cost analytic relationship.

Goals and Targets Seventeen of the 20 state DOTs that responded to this question indicated that they define targets for their levels of service or performance measures. Agencies considered one or a combination of factors (with four being the maximum) in setting the values of these targets. The factors are listed with corresponding numbers of responses in Table 2. Additional comments by survey participants were as follows:

- One agency reported that its budget model for field maintenance (excluding operations work) was capable of estimating a budget-constrained LOS target as a function of the particular assets or features involved, the existing LOS, the asset inventory, and the average cost per inventory item to perform maintenance work. Unconstrained targets could also be estimated.
- A second agency described its business process: The M&O Branch Manager makes recommendations to the Transportation Commission which then sets the target LOS for M&O to attain. This target translates as well into a budget to reach that target.
- A third DOT reported that a few selected measures are part of the agency "performance plan" that is submitted to the state's Department of Management as part of a statewide "accountable government" program.
- Other agencies described a variety of ways in which targets were developed: e.g., based on needs as determined by engineering judgment, engineering analysis, or market research; as a function of projected budget; and as a commitment to meet an agency-established objective or goal. One of these agencies noted that a gap analysis (between conditions and targets) is used to track whether the targets are realistic given the existing conditions, priorities, and budget.

TABLE 2 Survey Results: Setting Goals and Targets

Factors Considered by State DOTs in Setting Targets	Number of Responses
As a function of projected M&O budget.	9
As a legislatively mandated agency commitment.	2
As an agency commitment under a state government accountability initiative.	2
Solely as a commitment to meet an agency-established objective or goal.	7
As a result of internal management or engineering analysis indicating a realistic target for accomplishment.	6
By another method.	6
No response.	1

Note: Respondents could select more than one choice above.

Developments in Operations Activities State DOTs were asked about innovative performance measures and levels of service they may have defined specifically for operations activities: e.g., winter maintenance, intelligent transportation system (ITS) devices, traffic signal systems, and incident response. Only nine state DOTs of 20 potential respondents answered this question affirmatively. Examples of innovative features and characteristics that were stated as part of the survey question were as follows, including the number of responding agencies for each.

- Winter maintenance: e.g., definitions of winter storm indexes or of "standard winter storms" (four agencies).
- Traffic signal system measures (three agencies).
- ITS device and other intelligent technology measures (one agency).
- Electronic system and environmental sensing system measures (one agency).
- Incident or emergency response measures (one agency).

Other examples that were provided by three respondents included a measure for traveler information (511 calls), a Work Zone and Highway Safety measure, and a winter performance measure using traffic speed and post-storm speed recovery time to evaluate maintenance performance.

Other Survey Findings

Apart from the results for the three survey questions above, other findings of the survey included the following:

- A performance-based approach is used to address a wide range of highway features. Prevalent among these are road surfaces, bridges, pavement markings, drainage features, road signs, guardrail, and roadside and median vegetation, among others. Other items are represented to a lesser degree, e.g., ITS devices, structures other than bridges, and roadway lighting, among others. In addition to highway features or assets, maintenance and operations services—e.g., incident or emergency response and winter maintenance—may also be addressed through a performance-based approach.

- In most cases maintenance and operations services are delivered under the auspices of the state DOT using its own employee work forces, contractors, volunteers, or prison labor. In only a few instances are other governmental levels (e.g., municipalities or counties) used for service delivery. In most cases where other jurisdictions are involved, overall program delivery is performed by a combination of state and local forces, and the state retains the responsibility for monitoring the LOS that is delivered. Wisconsin DOT is unique in contracting all of its maintenance and operations activities with Wisconsin counties, although Wisconsin DOT monitors the LOS delivered.
- Performance measures and LOS thresholds currently tend to be defined on a uniform statewide basis. Some variability is allowed for in activities influenced by weather (e.g., winter maintenance) or by traffic volume and degree of urbanization. A unique approach has been adopted by Caltrans in defining zones within the state to account for varying traffic volumes and terrain combined. State DOTs may be willing to consider introducing additional variability in thresholds when the pool of accumulated performance data is deeper.
- Inspections to determine field conditions that support the performance-based approach are conducted in various ways with no particular method predominating. Many state DOTs use a combination of central-office, district, and third-party teams to accomplish data gathering.
- Twelve of 20 responding agencies addressing this issue solicit feedback from customers through a variety of ways, with telephone or mailed surveys being the primary methods. While some survey efforts are relatively broad and infrequent, others are directed specifically to maintenance and operations issues, and agencies on average employ more than a single method to obtain this information. Several agencies report using web-based technology to solicit customer assessments and opinions online. Only a few agencies solicit input from industry groups.
- Just over half of the responding agencies apply performance-based measures to contracts, often using the same LOS or performance measures as those applied to in-house forces doing comparable work.
- Agencies view communication of performance-based information as important, whether it concerns information prior to a decision or the consequences that may result following a decision. Most respondents identified five entities most often involved in communications of performance-based accomplishments or accountability: personnel within the DOT itself, the Transportation Commission or equivalent, the legislature, the governor, and the general public. Other recipients are involved less often: e.g., other state agencies, industry groups, the FHWA, and so forth. Several mechanisms are used for communication, but the two reportedly used the most are performance accomplishment reports and dashboards presenting conveniently summarized information.

Case Examples

Whereas the survey was intended to capture a broad picture of nationwide practices, four case examples of particular state DOTs were developed to illustrate applications of their performance-based approaches to specific management situations. Two cases (Mississippi DOT and Wisconsin DOT) illustrated business processes in developing and sustaining performance-based methods, with the remaining two cases (Florida DOT and Washington State DOT) demonstrating specific management tasks employing performance-based methods. Following are thumbnail

summaries of each case. The full descriptions of each case are presented in *NCHRP Synthesis 426* (*1*).

- The Mississippi DOT case illustrated the process used to implement a new performance-based approach accompanied by introduction of a new maintenance management system, AMMO (Accountability in DOT Maintenance Operations). Mississippi DOT employed consultants and vendors to guide the two prongs of its new performance-based approach: identifying and instituting new business processes, and customizing, developing, testing, and implementing new AMMO software. Pilot testing was useful in merging these two efforts correctly, verifying AMMO accuracy, familiarizing DOT personnel with the system, and identifying training needs. This approach to implementation represented a process that was thought-out ahead of time with the aim that all pieces fit together properly.
- The Wisconsin DOT case focused on processes and procedures undertaken to keep its performance-based M&O system, Compass, current and prepared to address program management tasks. The processes and procedures reviewed included field rating procedures, assigning priorities to highway features, quantifying LOS thresholds and grading curves, setting and communicating targets, and so forth. In part because Wisconsin DOT and its five regions deal with 72 counties who are the performing organizations for state highway maintenance in Wisconsin, Wisconsin DOT places a premium on good communication, coordination, effective data to support decisions, and shared responsibilities between the state and county participants.
- The Florida DOT case looked at how maintenance activities are prioritized for accomplishment throughout the year to ensure that the accepted statewide maintenance standard is met on all state highways. Florida DOT applies its Maintenance Rating Program, MRP, to determine condition-based scores for each characteristic of its highway elements throughout the year. The department combines this objective, analytic basis for determining the status of planned versus actual condition with a managerial check, the Quality Assurance Review, which seeks to ensure that funding is actually redirected to those activities that will produce positive performance results with respect to a mandated statewide target in the following period.
- The Washington State DOT case illustrated the application of its Maintenance Accountability Process (MAP) data to support meeting the requirements of Washington State DOT's Phase II stormwater permit. MAP data on service levels for affected drainage features have been incorporated directly within the permit's language to discuss the performance and maintenance level-of-effort implications of the permit requirements, to indicate how compliance with the permit would be monitored through MAP inspections and reports, and to establish the basis for a request to the legislature for additional funding to comply with permit requirements.

Template of Performance-Based Highway M&O Management

Agencies with mature performance-based approaches have developed methods to illustrate the relationships among M&O LOSs, annual M&O investment levels, and performance-based implications. Washington State DOT and Wisconsin DOT, both of which employ graded LOS approaches in their M&O programs, have each produced a graphic showing these relationships. The two agency graphics are similar but include different performance-based implications or outcomes. For purposes of this study, the two graphics have been consolidated into a single, unified diagram as shown in Figure 2. While not every agency has adopted this type of LOS, the

diagram serves as a useful template to illustrate performance-based concepts as applied to highway M&O management.

The upper part of Figure 2 relates LOS to the level of annual M&O investment. LOS A is the superior level of maintenance, and entails a greater annual investment to achieve superior quality, coverage (e.g., percent of the total highway network assets), and frequency of performance. Conversely, LOS F is a minimal level of maintenance, funded at a lower annual investment. LOSs B, C, and D are intermediate values lying between these two extremes in both funding and maintenance quality, frequency, or coverage.

The lower part of Figure 2 illustrates performance implications or outcomes resulting from the level of annual M&O investment and the resulting delivered LOS. Two sets of outcomes are shown: those relating to the M&O program itself, and those related to impacts on the transportation system. A line is used to represent each type of outcome, representing a spectrum or continuum of possible values of that outcome. On each such line, moving to the left entails outcomes of greater investment and better quality maintenance and operations; moving to the right incurs outcomes of lesser investment and poorer quality maintenance and operations. The set of outcomes shown is not exhaustive, but is sufficient to get the idea across. Also, these outcomes must be viewed in the context of typical agency stewardship of a highway system, and the technological limits of maintenance itself. Thus, in the M&O program outcomes, maintenance work can extend the lives of highway assets and enable them to perform acceptably for longer periods of time, but it cannot do so indefinitely. Eventually, the ravages of time, materials aging, weather, continuous traffic loading, structural fatigue, and catastrophic events, among other factors, take their toll, and assets must be rehabilitated, reconstructed, or replaced. In the transportation system outcomes, both capital construction and M&O actions determine the overall performance of the transportation network. Network performance is not due to the level of maintenance and operations alone. Therefore, with both types of performance implications, the values of outcomes discussed should be interpreted in relative rather than absolute terms.

The outcomes related to the maintenance and operations program include not only matters of quality, coverage, and frequency discussed above, but also the character of the maintenance that can be systematically performed (whether preventive/ proactive, or corrective/ reactive), the relative cost-effectiveness of the M&O actions and services, and the range of priorities able to be addressed. For example, a level of investment gauged to LOS A enables an agency to address a fuller range of priorities encompassing critical work such as safety or maintenance of critical infrastructure, as well as less critical priorities such as roadside appearance. By contrast, lower LOS values and lower levels of annual investment imply budget constraints that limit the scope of work priorities to critical repairs, actions, and services.

Similarly, in the transportation performance implications, M&O investments and levels of service influence a number of basic outcomes:

- Safety, which is promoted through properly functioning signals, signs, pavement markings, roadway lighting, advance warning devices, ITS devices, roadway and roadside safety hardware, and effective response to roadway incidents.
- State of repair of highway assets, which respond directly to the frequency, coverage, and quality of needed preventive maintenance and corrective repairs, which can extend the lives of assets and enable more reliable operation.
- Reliability of system mobility, which is promoted through well maintained facilities that facilitate safe and efficient traffic movement.

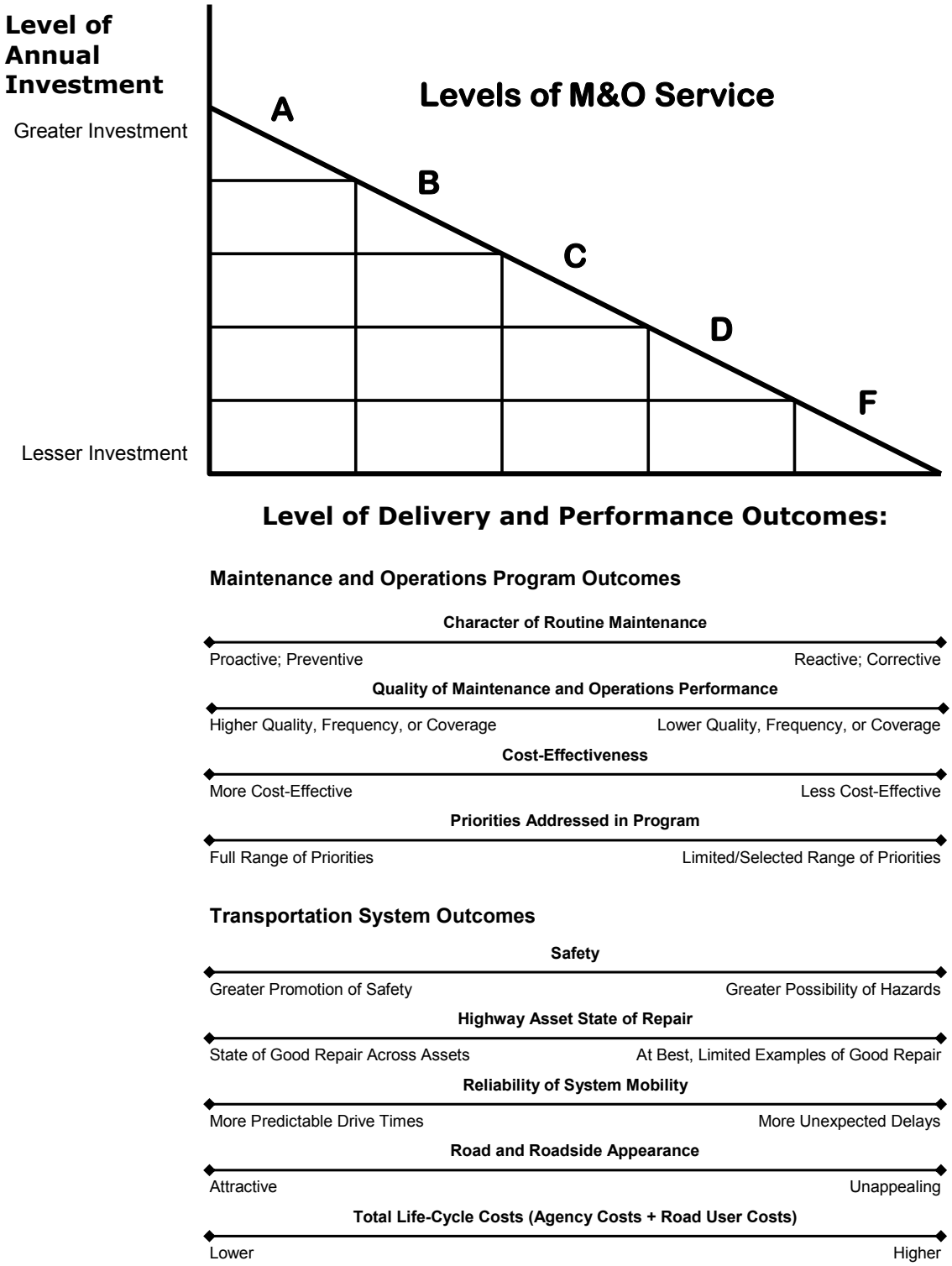

FIGURE 2 Maintenance LOS, level of investment, and performance impacts (*6*, *7*).

- Road and roadside appearance, which can increase road user comfort and pleasure.
- Total life-cycle costs of highway transportation, which includes road user costs as well as agency expenditures for highway construction, rehabilitation, and maintenance and operations. Higher M&O LOSs and related expenditures can help minimize overall life-cycle costs through reductions in road user costs (due to better mobility and safety) and reductions in agency costs (due to life-extension of highway assets).

AGENCIES NOT NOW USING PERFORMANCE-BASED METHODS

Ten agencies responded in the survey that they do not now use performance-based methods to manage their maintenance and operations programs. Eight of these state DOTs provided explanations of alternate management approaches they now use, selected from a list of possibilities provided in the questionnaire. All of their responses focused on four alternate management approaches:

- Annual programs are tailored to funding availability, irrespective of inventory, condition, or performance (six responses).
- Annual programs are based upon previous year plus specific adjustments (five responses).
- M&O work is being deferred, with a focus on critical items only (four responses).
- Annual programs are based primarily upon inventory quantities and percentage inventory maintained each year (two responses).

The eight responding agencies cited either one or up to three methods in combination that they use to manage their M&O programs; funding availability was included most often in the responses, as noted above. The same eight agencies also listed what they perceive as reasons for not moving to a performance-based approach. Most agencies cited two or three reasons in combination for not having moved to performance-based M&O management, with an evolving management approach and insufficient resources being the most prevalent. The one agency that cited a single reason selected insufficient resources. No additional comments or other factors were provided by these respondents.

CONCLUSIONS

This paper has considered the characteristics of performance-based management of highway maintenance and operations as practiced by U.S. state DOTs. In contrast with past research that has tended to focus on the elements of performance-based methods—condition measurement, performance measures, construction of LOS measures, and so forth—this study has sought to understand the relevant management processes themselves. It has done so for two business environments: the processes needed to initiate successful performance-based efforts and to sustain them year after year, and the range of management tasks to which performance-based methods can be applied by M&O organizations. This information has been developed through an NCHRP highway synthesis project in which data were gathered in two ways: a survey of state DOTs to establish broad national trends, and development of focused case examples with the

cooperation of four state DOTs that either already have mature performance-based programs or have just successfully developed a new program.

While the various implementations of performance-based M&O management differ in their details, the survey results indicate general agreement on key aspects of management technique and supporting activities. For example,

- Performance measures and LOSs thresholds currently tend to be defined on a relatively uniform statewide basis, with variability introduced for factors such as differences in weather, traffic volume, and degree of urbanization.
- State DOTs tend to look to several management tasks in common to be supported by performance-based methods, e.g., tracking condition, performance, and quality; M&O prioritization; budget development and justification; development of needs-based management estimates; resource allocation among field offices; and an understanding of the relationship between LOS and cost.
- The majority of respondents identified a cluster of factors that are important in setting LOS targets: the projected M&O budget, commitments to an agency-established goal or objective, and analytic estimates of LOS values that are realistic to attain and sustain.

Four case examples reinforced and built upon the findings of the survey to illustrate how individual performance-based elements come together and are applied by agencies to different management needs and tasks. Two cases dealt with processes and procedures needed to build and sustain the performance-based approach itself, and two dealt with application of the approach to M&O program management. Mississippi DOT and Wisconsin DOT were the subjects of the process-oriented cases; Florida DOT and Washington State DOT, the subjects of the program-oriented tasks. These cases illustrated the versatility of performance-based methods in managing the highway M&O program and in addressing other policy and management issues that affect highway maintenance and operations (i.e., the stormwater permit case illustrated for Wisconsin DOT).

ACKNOWLEDGMENTS

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PERFORMANCE MEASURES, DECISION SUPPORT, AND
RISK MANAGEMENT IN HIGHWAY MAINTENANCE

Best Practices in Highway Maintenance Performance Measuring

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As transportation agencies have shifted their focus from system expansion to system preservation and maintenance, they have increasingly turned to maintenance quality assurance (MQA) programs to document the effectiveness of their maintenance activities, to demonstrate that funds for maintenance and operations are being used effectively, and to link performance data to budget requirements to meet targeted condition levels. In the fall of 2011, a domestic scan took place to study the use of MQA programs for maintenance and operations activities. The scan used a workshop approach that allowed participants from 17 state highway agencies to discuss their current MQA practices. Eight different sessions were conducted, addressing a range of topics, including MQA data collection methods and measures and the validation methods used to ensure data reliability. The impact of sampling on data quality and cost was also discussed, as was the use of innovations in data collection. Other sessions focused on the use of MQA data for setting budgets and allocating resources, building accountability both internally and externally, calculating trade-offs in maintenance and capital expenditures, and benchmarking practices across agencies. This paper summarizes the results of the scan in each of the topic areas addressed and presents overall findings from the discussions. In addition, the paper presents the scan team's recommendations for advancing the state of the practice and strategies for implementing the recommendations.

Preserving and maintaining the condition of highway assets is a key component to enable state highway agencies (SHA) to provide a safe, smooth, and sustainable transportation system. While the construction phase of a highway life cycle often receives the most attention from elected officials and the public, responsibility for maintaining the roadway infrastructure assets is typically the longest of the phases of the highway life cycle and one of the most important factors in determining the frequency with which assets need to be reconstructed or replaced. As many transportation agencies have realized, ongoing investments in planned maintenance activities are a cost-effective way to postpone more costly treatments down the road and an important strategy for achieving customer satisfaction with the road system.

Because of the importance of maintenance and operations activities to a highway agency, there have been numerous initiatives designed to improve quality and to better defend budget requirements. Maintenance quality assurance (MQA) programs first emerged in the late 1990s as a method of assessing and documenting maintenance quality. In their infancy, these programs were focused primarily on documenting work accomplishments to report the resources used and production rates and reporting planned versus actual accomplishments. Within the past 10 years or so, these programs have become more customer oriented with an increased focus on maintenance outcomes and targeted performance levels. As a result, several SHAs are using their

MQA results to set performance targets and to estimate budgets needed to achieve the performance targets. Consequently, these agencies can better defend budget requests, establish maintenance priorities, and demonstrate the impact of different investment levels on maintenance quality than they could in the past.

To date, there has been a great deal of variability in how agencies have established these MQA components and how the results have been used to establish accountability, to improve maintenance effectiveness, to establish budget requirements, and to allocate resources. For instance, some agencies utilize a pass–fail approach to assessing the condition of its features, while others measure deficiencies and report conditions in terms of a level of service (LOS). Additionally, a number of agencies use a sampling approach to represent overall maintenance conditions, while other agencies collect condition data on each asset in the network. Further, some agencies collect data manually while others make use of digital images collected by automated data collection equipment. Together, these differences have a tremendous impact on the resources required to support an MQA program and the degree to which the information can be used for budgeting and resource planning.

The maintenance community is fortunate in that there have been several peer exchanges in which practitioners have had the opportunity to come together to discuss their MQA programs and practices. Most recently, the North Carolina Department of Transportation (DOT) hosted a peer exchange in 2008. Prior to that meeting, the Midwest Regional University Transportation Center at the University of Wisconsin–Madison (now the Wisconsin Transportation Center) hosted a peer exchange in 2004. In association with each of the peer exchange meetings, the University of Wisconsin collected and posted MQA manuals and other information provided by the states on a website.

While the MQA website has proven to be a useful resource for maintenance practitioners, additional information is needed to enable agencies to determine the advantages and disadvantages of the various options available to them as they initiate or enhance their efforts to better use maintenance performance data for the maintenance and preservation of highway assets. Therefore, a domestic scan was organized through the U.S. Domestic Scan Program managed under the auspices of the NCHRP. A scan team was selected by AASHTO and NCHRP to establish the scope of the scan and to identify the agencies that would be selected to participate in the scan. These efforts were supported through the selection of a facilitator–report writer who conducted a desk scan of current practices in this topic area and who recommended agencies that had established strong practices in the topic areas established by the scan team.

The domestic scan took place in October 2011 in Anaheim, California. It was structured in a peer exchange format, providing an opportunity for representatives from 17 SHAs to participate in discussions structured around the following topic areas:

- Establishing reliable and cost-effective methods of monitoring the quality of maintenance and operations activities;
- Using MQA data to establish accountability with internal and external stakeholders; and
- Using the MQA results to set budgets, establish performance targets, allocate resources, justify needs, establish strategic plans, monitor customer satisfaction, and measure contributes to an agency's strategic performance targets.

The scan was conducted over a 3-day period with sessions organized to examine the organizational and institutional structures, programs, policies, operational practices, and delivery mechanisms that have enabled agencies to successfully use performance-based management practices for highway maintenance and preservation. Specific objectives for the scan included the following:

- Explore the experiences of top-performing agencies, examining the degree to which agencies' business plans and system preservation strategic plans are linked to their MQA programs;
- Identify successful strategies for linking customer expectations to agency performance measures;
- Examine the variables that have most influenced the use of MQA results to improve agency accountability or to support budgeting and resource allocation decisions;
- Examine if and how different data measures, data collection procedures, and data verification activities influence MQA program costs and the use of MQA results;
- Examine ways in which innovation has been incorporated into MQA programs;
- Explore the ways highway maintenance and preservation information is presented to senior management, elected officials, and the public;
- Explore the strategies, such as education and training programs, that have been used successfully to build buy-in and accountability among field personnel; and
- Identify technical or organizational challenges to overcome and strategies to improve the use of performance measures for highway maintenance and preservation activities.

The results of the scan are documented in a final report. This report summarizes the initial findings from the scan and the scan team's recommendations for further action to further promote the use of performance-based data to support the effective maintenance and operation of highway assets.

SCAN TEAM MEMBERS AND PARTICIPANTS

Russ Yurek, Director of the Office of Maintenance for the Maryland SHA, was selected to represent the scan team as the chair. Other members of the scan team included

- Lonnie Hendrix, State Maintenance Engineer for the Arizona DOT;
- Nancy Albright, Director of the Division of Maintenance for the Kentucky Transportation Cabinet;
- Don Hillis, Assistant Chief Engineer for the Missouri DOT;
- Jennifer Brandenburg, State Road Maintenance Engineer for the North Carolina DOT;
- Matt Haubrich, Asset Manager for the Iowa DOT Office of Maintenance; and
- Luis Rodriguez, Pavement Management Engineer for the FHWA Resource Center in Atlanta, Georgia.

The scan team also included a facilitator–report writer and a contractor who organized and administered the scan activities.

Based on the results of a desk scan of current practices, 13 SHAs were invited to participate in the scan. The invited agencies represented a range of different approaches to assess, report, and use maintenance performance data to support the maintenance and preservation of highway assets. Although some of the invited agencies (the Virginia and Georgia DOTs) were not able to participate due to travel restrictions or other conflicts, a broad representation of SHA practices were represented by the scan participants. The following agencies sent representatives to participate in the meeting:

- California DOT (Caltrans),
- Florida DOT,
- Kansas DOT,
- Minnesota DOT,
- New York State DOT,
- Ohio DOT,
- South Carolina DOT,
- Texas DOT,
- Utah DOT,
- Washington State DOT, and
- Wisconsin DOT.

DISCUSSIONS

The 3-day scan consisted of eight sessions, each of which focused on a different aspect of the use of performance data for the maintenance and operation of highway assets. The discussions and findings that took place within each of the eight topic areas are presented in this section of the paper.

Session 1: Advantages and Disadvantages to Pass–Fail and LOS Approaches

There are three predominant approaches being used to monitor and report maintenance quality: the pass–fail approach, the LOS approach, and an approach that combines the two. Agencies using the pass–fail approach define deficiency criteria for each asset being inspected. For instance, a guardrail may be considered to be deficient if 10% or more of the guardrail length is not performing as intended. During the MQA inspection, raters count the number of guardrails that either pass or fail based on the criteria established. This approach is relatively quick and easy to conduct in the field, which is why some agencies prefer this approach. The biggest disadvantage to the pass–fail approach is that the ratings provide no information with regard to how close a guardrail was to passing or failing. For instance, the survey does not indicate whether 12% or 100% of the guardrail was deficient. Therefore, while the survey results can be used to report guardrail condition, it is difficult to use the information for budgeting and scheduling maintenance repairs. Additionally, if the definition of a deficiency changes all the guardrails must be reinspected to determine the condition under the new criteria.

To address these limitations, many agencies have moved towards the use of a graded LOS approach, in which the amount of a defined deficiency is recorded in the field in accordance with pre-established criteria. Since this approach requires that the amount of a deficiency is

estimated, it takes longer to conduct this type of survey than it does to conduct a pass–fail survey. However, the information provides the data needed to estimate work quantities for budgeting and for maintenance planning. Other agencies have adopted a hybrid approach that combines the best features of each of the two approaches.

These topics were discussed by the scan participants and the some of the points raised by the participants are provided. They illustrate that agencies can successfully use MQA data regardless of the approach used. However, having upper level support for the program, or legislation mandating the use of condition data, can be an important consideration in the program's success.

- Legislation in Florida, North Carolina, and Washington State has promoted the use of MQA programs. For instance, in Florida the state legislature mandates a minimum maintenance rating of 80. In North Carolina, the DOT is required to report maintenance needs every other year. In Washington State, the maintenance accountability process began so the DOT could respond to the legislature's question as to how funds were being used.
- There are advantages and disadvantages to both the pass–fail and the LOS approaches used to report asset conditions. To minimize the disadvantages of these methods, some agencies have adopted hybrid approaches that combine the best features of each approach. It appears that the reasons for moving to a LOS approach are not well understood; therefore, agencies are not inclined to shift from their pass–fail or hybrid approaches.
- Some agencies avoid using the terms pass and fail because of negative connotations associated with the term "fail." Instead, agencies like the Florida DOT and Caltrans use terms like "meets" or "does not meet" performance standards.
- Regardless of what approach is used, it is important to have shadow programs or other methods of ensuring consistency and data quality. The scan results indicate that there are many formats that can be used for this activity. For example, the New York State DOT uses a shadow program to help ensure data quality, the Texas DOT has established a ride-along program, and the Wisconsin DOT relies on its training and rating manuals.

Session 2: Impact of Agency Approach to Sampling on Quality, Cost, and Use of Data

Collecting the data to support a MQA program can be very demanding in terms of the resources required. For that reason, some SHAs have elected to collect data on a sampling basis rather than collect data on the entire asset inventory. With this approach, a statistically representative number of samples are randomly selected and inspected. The results are aggregated and used to represent conditions at a state, regional, or district level. The presentations and discussions on this topic area included the points listed below.

- There are many commonalities between the types of features that are rated as part of the MQA programs used by the participating agencies.
- Most states can only afford a sampling approach, although there are exceptions (e.g., Utah and Ohio). There are pros and cons associated with both sampling and with collecting data on the entire network. Each agency must consider its own situation to determine a sustainable approach to data collection.

- At a minimum, agencies inspect the lowest number of samples required for the survey to be statistically valid, but the Texas DOT surveys additional samples to help reduce variability in the data.
- There does not appear to be a consistent methodology for handling underrepresented assets in inspections (e.g., signs). In some agencies, such as the Iowa DOT, there is interest in having access to guidelines for handling these types of assets.
- Both windshield and walking surveys are being used by participating agencies. The selected approach depends on a number of factors. In the Maryland SHA, for example, the agency selected a windshield approach because they feel it best represents what most customers see.
- Quality assurance activities have helped with consistency in the ratings used by the Utah DOT. The Wisconsin DOT indicated that the information from quality assurance activities can also be used to identify suggestions for improving training or for improving the survey procedure itself. Interestingly, the Utah DOT found that data quality is more influenced by the budget process than by the sampling approach used.
- The cost of collecting data for MQA programs is insignificant when compared to the impact the results can have on maintenance budgets. The Utah DOT, for example, spends less than 1% of their maintenance budget on these activities. The Washington State DOT spends about $400k annually, as does the Iowa DOT. The Arizona DOT spends about $300k each year on data collection activities.
- The level of detail collected in the surveys impacts how agencies are able to use the data. For instance, the Utah and North Carolina DOTs can make budget decisions using the data because of the number of samples they inspect. Other agencies, such as the Kentucky DOT, report data at the district level, rather than any smaller subset level, because of the number of samples they inspect. The level of reporting has a tremendous impact on the amount of data required, as evidenced by the approximately 23,000 samples surveyed by the North Carolina DOT every 2 years.
- Some agencies don't collect data on assets that are being inspected as part of other programs. For instance, the North Carolina DOT uses the results of pavement management surveys for their pavement LOS ratings.
- Several agencies, including the Caltrans and the Texas and Maryland DOTs, were able to increase their sampling rate without increasing direct costs. For instance, the Texas DOT accomplished this by using a 2-year average condition rather than a single-year rating.

Session 3: Use of Innovations in Data Collection

Since data collection activities can be labor intensive, it is important that available technology is used as much as possible. Some of the innovations that have been used by the agencies participating in the peer exchange are provided.

- In the South Carolina DOT, innovations in data collection, such as setting performance goals for each individual and unit, have doubled productivity and led to an improvement in accuracy. In the Ohio DOT, the use of a touch screen program has enabled them to have data available within 2 weeks after the surveys are conducted. They have also reduced costs by using hybrid vehicles.

- Handhelds proved to be more accurate than and just as timely as automated data collection vans in a pilot study conducted by the Utah DOT. Therefore, agencies can establish a good part of the inventory fairly inexpensively and sometimes older technology can be just as effective.
- Working with an information technology (IT) department can be a challenge. However, to build a strong teaming relationship each party has to recognize the skills that the other group brings to the table. In the Missouri DOT, for example, they had IT staff working in the maintenance department to help identify and articulate needs. This helped get things through the hierarchy.
- Most participants in the scan would collect more data if they could afford it, could get it quickly, and could get better quality or better use it to influence decisions.
- The Utah DOT fosters a leading edge culture that has enabled them to test new innovations fairly easily. This has benefitted the program because of the ease with which new technology can be integrated into the program.
- When collaborative methods are used to build inventories, guidance must be developed to clearly specify how the baseline inventory will be maintained over time so that all parties know who is responsible for each type of data.

Session 4: Use of MQA Data for Maintenance Budgeting and Resource Allocations

Traditionally, an agency's maintenance and operations budget has been developed based on historical budget levels that are increased or decreased to match available funding. However, some of the agencies who participated in the scan have been able to use their MQA results to conduct performance-based budgeting.

- Some agencies, such as the Maryland SHA and the Kentucky DOT, have been able to use their data to allocate funds to address their backlog or to address a higher-level (statewide) need. The New York State DOT was able to use the data in a similar fashion for drainage needs.
- The Texas DOT has a focus on pavement that is known as "pennies to the pavement." Under this program, people are held accountable for projected conditions that should be achieved with the funds provided.
- Several agencies, including the Washington State and Texas DOTs, have used their needs estimates to obtain additional funds.
- In recognition of the increased demand that capital improvements have on maintenance, Washington State DOT conducted a baseline analysis to show the legislature the impact of new miles on future maintenance needs.
- At least 11 of the participating agencies (i.e., Kansas, Ohio, Wisconsin, North Carolina, South Carolina, Maryland, Iowa, Missouri, California, Florida, and Texas) roll up their results into a single statewide maintenance score with weights to reflect priorities.
- Agencies use a variety of techniques for budgeting maintenance activities and for estimating maintenance needs. For example, the Texas DOT uses a needs-based budgeting approach while the Florida and Utah DOTs uses a zero-based budgeting approach. The other participants use more of a formula or history-driven budgeting approach. For the most part, agencies are not using MQA results to manage maintenance funds across districts. Instead, the results are used to make better use of funding within a district. However, the Washington State DOT is moving towards a more integrated needs-based budget.

- Good performing districts tend to feel short-changed when money is solely allocated based on the gap between targeted and actual condition. An analysis of the data to determine the factors causing the gap is important to address these concerns. Steps should also be taken to help people avoid future gaps in performance when the gaps can be eliminated by improving the manager's decisions. It is also important that corrections be made to high-priority features.
- MQA programs don't drive policy. Rather, they evaluate compliance with policy and the consequences of policies. This difference is emphasized in the training conducted by the Wisconsin DOT. The New York State DOT has used graphs to illustrate the consequences of new policies being considered by the agency.

Session 5: Linking Customer Expectations with Performance Targets

Today's MQA programs are more customer oriented than programs established in the past. During this session, scan participants discussed strategies for linking customer expectations with their performance targets. Some of the findings from the discussions are presented below.

- There are different perceptions that must be considered in developing a maintenance program. For example, Kansas DOT found that customer survey results don't always match maintenance performance measures when they compared the traveling public's rating of guardrail conditions (high) with the MQA ratings (low). The discrepancy was related to the height of the guardrails, which did not match the DOT's guidelines.
- In customer surveys, the Missouri and Kansas DOTs both found that pavements always come out on top in a customer survey.
- DOTs increasingly use social media to communicate with stakeholders. For instance, the Missouri DOT has developed a "show me my buzz" app and the Minnesota DOT has developed an online community.
- Close working relationships with public information officers and market research personnel has strengthened several maintenance programs. The Minnesota DOT reports that they have full-time market research personnel employed in the DOT to help evaluate public response to changes in programs and policies. The Washington State and Texas DOTs have public information officer assigned to maintenance.
- Stewardship is based on a combination of technical expertise, strategic direction, and customer input. The weight of any of these factors may vary depending on the item or activity.
- What gets measured can influence behavior both positively and negatively.
- Most of the scan participants report that it is worth the expense to obtain customer feedback as long as the results are used.

Session 6: Strategies for Building Buy-In and Accountability Among Field Personnel

The quality of the data reported by field personnel is strongly influenced by their understanding of how the data will be used to support maintenance decisions. This session focused on strategies that participating agencies have used to build buy-in to help ensure the quality of the data reported in maintenance management systems. The significant finds from those discussions are presented below.

- There are many different strategies used to build buy-in among field personnel, including riding with raters, an approach employed by the Ohio DOT; getting employees engaged through competition, recognition, and bonuses, as employed by the Texas DOT; and holding employees accountable, as employed by the North Carolina DOT. Legislation and reorganization have also had a positive impact on gaining acceptance in the North Carolina DOT.
- Holding people accountable was a key to changing the culture in the Missouri and North Carolina DOTs. Other agencies report that educating staff about the way the data will be used can also be beneficial. The Kansas DOT reported that maintenance training benefitted their agency because maintenance priorities and practices were better understood.
- The New York State and Utah DOTs indicated that if the number of samples inspected during the MQA program are not significant enough to report out by maintenance shed or smaller units, it's easy for personnel to get the impression that MQA is a central office program and not useful for their purpose. This can impact the quality of the data entered by field personnel.
- The Texas DOT indicates that they found it better to conduct ratings using people not responsible for the maintenance of those sections, especially if ratings are used in evaluations or individuals are rewarded with incentives.
- Some, but not all, agencies resist using MQA results to evaluate personnel performance. Others, such as the Ohio and North Carolina DOTs, are using the results in individual performance assessments. Several agencies participating in the scan indicated that the ability to use MQA data for performance evaluations depends on how the program is structured. For example, the Kansas DOT uses MQA results to set performance targets for individuals that focus on actions rather than overall scores (e.g., increase the number of signs replaced from the previous year).

Session 7: Presenting and Selling Results

According to the participating SHA personnel, the most common use of the MQA data is to report conditions and to establish accountability with stakeholders. This session focused on strategies being used to present and sell the results of MQA programs in SHAs. The findings from those discussions are presented below.

- Maintenance has traditionally been behind other modes of transportation in "telling their story." The Wisconsin DOT has found that MQA programs have enabled maintenance to better communicate needs and trends, while also improving accountability and decision making.
- Maintenance personnel do not always understand the need for MQA programs. However, by promoting these tools as methods of communicating needs and "telling the story" agencies can begin to establish buy-in from these groups.
- Agencies that do not have legislated programs or strong executive support have used MQA data as "targets of opportunity." In other words, they look for opportunities to show how the data can be used.
- Maintenance serves a large number of stakeholders and each has different interests and different level of knowledge. To be most effective, messages must be tailored to each group.
- MQA results are typically reported annually. In Washington State DOT, for example, the Grey Notebook is a departmentwide report that is produced quarterly. Even though the report

is published quarterly, the maintenance measures are only reported once each year in the December report.

Session 8: Emerging Technology

The development of new technology provides opportunities for enhancing existing MQA capabilities. During this session, participants discussed the use of emerging technology to support the use of performance data in maintenance planning and budgeting activities. The results of the discussions are presented below.

- The Ohio DOT has improved consistency in linking location and condition data by providing field personnel with PDAs that have a map interface.
- Some agencies are already making use of new technology such as iPods and tablets.
- There are significant opportunities to take advantage of new technology for data collection, integration, analysis, and outreach.
- Global positioning systems and other technology are changing so quickly that purchasing equipment is very frustrating in SHAs. By the time DOTs study the technology and have gotten it through procurement, they're already a generation or two behind.
- Data integration is very important to the success of a MQA program. Geographic information systems (GIS) are becoming the most common way of integrating data. Even though the Texas DOT is still using reference markers, the existing management system can convert data so it can be reported in the GIS.
- Automated vans are used for data collection associated with building asset inventories in the Kentucky and Missouri DOTs, but it is not commonly used for assessing maintenance conditions. The New York State DOT is going to explore this in its new contract with a vendor and the Utah DOT is conducting an expo to explore real-time sign recognition capabilities.
- While most agencies are using common business processes (loosely), there are differences in how these processes are applied. However, there is a strong interest among practitioners to share experiences so they can learn from their peers.
- Early leaders in MQA are at the point that their systems require advancements to continue to meet their needs. However, their prior efforts have made it easier for other agencies to use the technology in the future. For example, efforts by the North Carolina and Kentucky DOTs to use SAP will likely benefit other agencies looking for similar types of capabilities.
- In general, agencies that want to conduct ad hoc queries of data currently require that individuals have the skills necessary to develop the queries. Peer exchange participants indicated that it would be helpful to have software tools that enable more automatic analysis of the data without relying on individuals to create the queries.
- The creation of data warehouses is a very time-consuming activity and it requires strong IT support. However, efforts to increase the accessibility of data within a DOT are generally beneficial.
- There is a need to better leverage maintenance data with other internal and external users.
- There is a tendency to move to the newest technology, but there is always a need to justify the benefits and compare that to cost.
- Graphics are more easily used to make connections to the data.

SUMMARIZED FINDINGS

Based on the information presented during the scan in each of the topic areas, several significant findings can be made. These findings represent the current state of the practice in the use of performance measurement for highway maintenance and preservation activities.

1. Performance-based data, such as the inputs to MQA programs, provide the foundation for assessing maintenance needs and for reporting results in all of the participating agencies. Several of the participating agencies have successfully used their MQA results to secure additional funds and to improve communication with both internal and external stakeholders.
2. The most successful agencies have established organizational cultures that support the use of performance data to drive maintenance and preservation decisions. Some of the participating agencies have been able to change their organizational cultures by holding people accountable for the decisions they make. Other agencies have used training programs effectively to help change the culture in support of performance-based programs and to build buy-in among field personnel.
3. There is no single approach that represents best practice in the use of performance-based data for highway maintenance and preservation. In practice, the intended use of the data drives the system requirements and the amount of data needed.
4. The quality of the data used in performance-based decision making is critically important. Therefore, the agencies represented by the scan participants have developed strong quality assurance programs to help ensure the reliability and completeness of the data.
5. Technology has had a significant impact on the efficiency with which data can be collected, integrated with other programs, analyzed, and reported. The South Carolina DOT, for example, reported that they doubled the productivity of their surveys and improved data accuracy by incorporating innovations into the data collection process. In a pilot study, the Utah DOT found that data could be collected using handheld tables as quickly and as accurately as with automated data collection vans, demonstrating that data can be collected very cost-effectively.
6. Most of the scan participants roll up their MQA results into a single statewide maintenance score with weights to reflect their agency priorities.
7. Some standardization in commonly used performance measures would facilitate the exchange of information among agencies and simplify the start-up activities in agencies that are just starting to build their performance-based programs. The availability of guidelines and training in this area would benefit the industry.
8. The cost of collecting data for MQA programs is insignificant when compared to the impact the results can have on maintenance budgets. The Utah DOT, for example, spends less than 1% of their maintenance budget on these activities.
9. It is important that there are links established between the performance data and budget changes. For instance, changes in budgets or standards should have a corresponding change in the LOS that can be achieved. This link establishes a connection between the performance data and agency decisions that is important for building buy-in and for justifying maintenance expenditures.
10. Additional efforts are needed to improve the methods used to report the results of performance-based programs to both internal and external stakeholders. Most of the participating agencies would welcome guidance on more effective strategies for reporting needs that will resonate with politicians.

RECOMMENDATIONS

Recommendations were developed for each of the topic areas explored during the scan. The scan team organized the recommendations into six activities that will promote and facilitate the use of a performance-based, customer-oriented approach for estimating maintenance needs and budgets, communicating with various stakeholder groups, improving the transparency of maintenance activities, and allocating resources effectively. Suggested actions within each of the six activity areas were also identified. The six activities and the action items include the following:

- Measure: Recognizing the national trend towards performance measures, initiate and lead activities that identify common performance measures that align with and contribute to high-level goals such as safety and pavement/bridge condition.
  - Elevate the importance of maintenance by establishing a link to the agency's asset management framework and strategic performance measures.
  - Charge the AASHTO Subcommittee on Maintenance (SCOM) with identifying commonly used performance measures in the areas of safety, asset preservation, environment, and mobility to support the development of national performance measures and that "measure what matters."
- Report: Identify communication and analysis tools that will enable maintenance agencies to better "tell their stories" and that moves the industry towards an open-architecture platform.
  - Conduct a study to evaluate the impact of maintenance performance measures on national strategic goals.
  - Develop methods of using technology and innovation to produce timely and actionable data or reports.
  - Promote mechanisms for sharing technology that establishes stronger collaborations between industry and the maintenance community, and speeds up the application of technology in transportation agencies.
  - Initiate research to develop deterioration models and/or life-cycle models for key maintenance assets and identify reciprocal relationships between capital investments (for preservation and expansion) and maintenance requirements.
- Improve: Develop strategies that improve the quality of data used for performance-based maintenance programs, including strategies that accelerate the use of new technology and innovation.
  - Document the benefits of MQA data collection activities to support the maintenance, preservation, and asset management needs of the agency.
  - Charge the SCOM with developing guidelines for data collection at various levels of sampling to ensure the statistical validity of the data and to evaluate underrepresented assets appropriately.
- Train: Develop and conduct training programs to support performance-based maintenance programs.
  - Review existing training programs and needs, assess gaps between the two, and support the development of new or modified training initiatives to address gaps.
  - Encourage federal support for sponsoring training and technology transfer activities to promote performance-based maintenance programs.

- Share: Develop a sustainable mechanism for sharing performance-based maintenance practices and experiences in state highway agencies.
  - Update and maintain the MQA website.
  - Develop guidelines illustrating how agencies can use MQA data to improve performance, support budgeting activities, build buy-in, and hold people accountable.
- Promote: Actively promote the use of performance-based maintenance programs among state highway agencies and develop strategies to increase the number of agencies using these programs.
  - Promote the best practices from this scan to state highway agencies and other transportation agencies and industry.
  - Document the contribution of performance-based programs to support asset management and agency preservation programs and demonstrate how agencies have successfully built collaborative programs.
  - Disseminate the results of current NCHRP research on promoting the benefits of maintenance.
  - Develop marketing material that agencies can use to promote and sustain the use of performance-based programs to decision makers.

PLANNED IMPLEMENTATION ACTIVITIES

The scan team also developed an implementation plan that will help promote the findings and advance the recommendations from the scan. The plan includes the following types of activities.

- Advance findings and best practices: The advancement of the scan findings will be accomplished through the following activities:
  - Update the MQA website: The MQA website maintained by the University of Wisconsin has not formally been updated since 2009 and the university is moving the site to a new platform. The scan team recommends that the site be updated with current information provided by scan participants and that the functionality of the site be improved to facilitate searches and other types of inquiries by practitioners.
  - Conduct a series of webinars on best practices: With support from the FHWA, the scan team intends to organize a minimum of two webinars during the 2012 calendar year to promote the findings and recommendations from the scan.
  - Present findings at technical meetings and conferences: There are a number of upcoming technical meetings and conferences at which the results of the domestic scan can be presented. Individual members of the Scan Team were assigned responsibility for presenting the scan results at the Annual Meeting of the Transportation Research Board, at various AASHTO meetings, and at the upcoming Maintenance Management Conference, the Transportation Asset Management Conference, the National Conference on Pavement Preservation, and the National Pavement Management Conference. Some funding to support travel to these events will be provided using project funds.
- Support the implementation of recommendations through AASHTO and FHWA: One of the most important ways to advance the recommendations from the scan is to promote the research and technology transfer initiatives through AASHTO and the FHWA. Therefore, assignments for working with various AASHTO committees and subcommittees were made to

members of the Scan Team. These efforts will help build support for the recommendations with AASHTO leadership and will promote research needs with the Standing Committees on Highways and Research.

- Develop plans for a technology exchange in 2013 or 2014 that demonstrates the use of technology and promotes a peer exchange: With funding support from FHWA and other industry partners, and with the support of the AASHTO Subcommittee on Maintenance, the Scan Team intends to promote the conduct of a peer exchange that promotes the use of technology in support of MQA programs and that further supports the sharing of practices among state maintenance personnel.
- Investigate the development of common performance measures for preservation, environment, mobility, and safety through the AASHTO Subcommittee on Maintenance. Indications are that future legislation may include national performance targets for highway preservation, environment, mobility, and safety. In anticipation, the scan team is interested in initiating discussion with members of the AASHTO Subcommittee on Maintenance to determine the consistency of performance measures currently being used for reporting maintenance conditions in these areas.
- Initiate evaluation of available training programs and needs and develop training to address gaps. Although there are a number of training programs available to assist agencies as they move forward with the development and implementation of performance-based maintenance programs, the options are not well known and gaps in coverage exist. Therefore, FHWA will summarize the training currently available and will identify any training gaps so that high priority training needs can be addressed.

CONCLUSION

The availability and use of performance data on highway assets is important to the effective maintenance and operation of highway assets. Over the years, MQA programs have emerged as useful tools to help agencies determine maintenance needs and priorities. By linking the performance data in an MQA program with budgeting tools, agencies have been better able to defend budget requests, establish maintenance priorities, and demonstrate the impact of different investment levels on maintenance quality than they could in the past.

To date, there has been a great deal of variability in how agencies have established these MQA components and how the results have been used to establish accountability, to improve maintenance effectiveness, to establish budget requirements, and to allocate resources. A 2011 domestic scan provided an opportunity to explore the differences in practices in 17 SHA. The results demonstrate that there is no single approach to using performance data for managing maintenance and operations activities. The agencies participating in the scan differed in the types of asset rating approaches used, the number of samples inspected, and the ways in which the data were used. However, in each of the participating agencies the availability of performance data served as the foundation for assessing maintenance needs and for reporting results to decision makers. The paper summarizes the findings from the domestic scan and presents recommendations to promote and facilitate the use of a performance-based, customer-oriented approach for estimating maintenance needs and budgets, communicating with various stakeholder groups, improving the transparency of maintenance activities, and allocating resources more effectively.

PERFORMANCE MEASURES, DECISION SUPPORT, AND
RISK MANAGEMENT IN HIGHWAY MAINTENANCE

Decision Support Technologies and Maintenance Management

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Decision support systems typically combine the use of computers, models, and appropriate data to support organizational decision-making activities. Department of transportation (DOT) maintenance decision makers have used decision support systems for winter maintenance activities for most of the past decade. In 2002, a group of states joined together [Pooled Fund Study Maintenance Decision Support System (PFS-MDSS)] to develop a MDSS that could augment current winter operation techniques with weather information and provide a one-stop shop for decision makers regarding snow and ice. As the acceptance of decision support systems by state DOT users has increased for winter operations, so has the desire to create new decision support systems modules for other maintenance activities. The second desire many users of MDSS have is to develop the ability of the system to integrate MDSS data with maintenance management data to reduce duplicate entry of these data and therefore improve efficiency and overall maintenance management. The use of MDSS for state DOTs has resulted in improved communications, more consistent levels of service, and, in most cases, an approved bottom line. The results in winter operations have created an aspiration for the same results in other state DOT maintenance activities including but not limited to herbicide spraying, pavement preservation, pavement repair, lane and intersection marking, and any other highway operation that is dependent on the weather and road conditions. Each operation has specific weather thresholds that will restrict or not restrict that specific operation's occurrence. Accurate weather forecast information is critical as many non-wintertime operations projects can be completely ruined or ineffective if precipitation occurs or if temperatures or moisture levels fluctuate quicker than expected. A maintenance and operations decision support system (MODSS) integrates appropriate decision weather thresholds for specific maintenance activities with weather forecasting and decision modeling to assist highway operation decision makers. The combination of improved weather forecasts with acceptable operating weather thresholds for non-winter maintenance activities provide agencies improved effectiveness and efficiencies when deploying a fully operational MODSS within their agency. Integration of MDSS, maintenance management and finally MODSS data is important to highway decision makers. Currently these systems contain similar data, but the data is not incorporated in one cohesive location, creating double and sometimes triple entry of the same or very similar information for each system. As MODSS becomes operational, and MDSS and maintenance management systems are being modified or advanced, consideration needs to be given to integration of the data shared between these systems. This presentation will cover how decision support can be used for non-wintertime maintenance activities. Data currently being used for winter operations decision support systems will be discussed for its usefulness in non-winter decisions. Examples will be presented assessing the use of MDSS for non-wintertime operations. The presentation will further investigate and discuss opportunities for integration of maintenance management data, MDSS data, and MODSS data for use in all systems.

PERFORMANCE MEASURES, DECISION SUPPORT, AND
RISK MANAGEMENT IN HIGHWAY MAINTENANCE

Public Works–Department of Transportation Role in Traffic Incident Management and All-Emergencies Response

DAVE BERGNER
International Municipal Signal Association

KIM VASCONEZ
Federal Highway Administration

The National Traffic Incident Management Coalition was initiated by the FHWA in 2004 to promote better communication, coordination, and cooperation among the disciplines considered as responders to major accidents on the nation's highways. Initially, the attention was on police, fire, emergency medical, and towing disciplines as primary responders; transportation, originally denoted as state departments of transportation (DOTs), was considered secondary. However, it is now acknowledged that many traffic accidents and other disruptions happen on local streets and roads under the jurisdiction of municipal public works (PW) agencies. PW and state DOT employees are well trained and equipped to handle temporary traffic control as part of their routine work. The other disciplines lack that same training and experience and do not have sufficient proper traffic control devices to handle large incidents. Though the other disciplines will need to be better trained and equipped for traffic incident management, their priorities will still be on attending to victims, conducting investigations, and clearing the scenes. Increasingly, they will then call upon PW–DOTs to handle the more extensive temporary traffic control situations. Thus, PW and DOT agencies need to better understand their evolving roles and responsibilities in traffic incident management (TIM). The protocols, relationships, and responsibilities used with TIM are actually based on National Incident Management System (NIMS) and Incident Command System (ICS). NIMS and ICS are employed for interdisciplinary and multijurisdictional response to other emergencies and events. Under Homeland Security Presidential Directive 8, PW is considered a "first responder" for all hazard occurrences. This is reinforced in other federal documents such as the National Response Framework and Emergency Support Function #1 and #3. It is possible that in certain situations PW–DOT could be designated as incident command. Therefore, working with the other first responder disciplines on TIM events provides opportunities to develop those key relationships and better define roles. In major disasters, such as hurricanes, tornadoes, floods, and earthquakes, PW–DOTs are needed in the short term to clear roadways, assist in search and rescue, provide traffic control and security, and transport people and supplies. For the long term, PW–DOTs continue with damage assessment, debris removal, repairs to infrastructure, and other matters. The speakers are members of the National Traffic Incident Coalition and each have extensive experience in traffic incidents and other emergencies and disasters. One is team leader with FHWA's Office of Emergency Traffic Operations and formerly worked for the Federal Emergency Management Agency. The other is a retired public works superintendent and was a traffic operations manager prior to that.

Bridge Maintenance, Inspection, and Management

BRIDGE MAINTENANCE, INSPECTION, AND MANAGEMENT

Determining the Items That Structure Bridge Management Components and Their Relative Weights

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A primary objective in bridge management is to ensure the optimal allocation of resources. This is especially true when bridges in a transportation network are continuing to deteriorate and available resources to address maintenance, rehabilitation, and replacement needs are limited. A common tool used by managers and decision makers to aid in determining how to distribute funds between competing bridges is a bridge management system (BMS). BMSs are designed to optimize the use of available resources for preservation and improvement of bridges. Recently, *NCHRP Synthesis 397: Bridge Management Systems for Transportation Agency Decision Making* investigated the current state of bridge management and how transportation agencies use BMSs to make decisions and identified concerns of inadequacy and ineffectiveness with bridge management and decision processes that only use a single value rating or index, such as PONTIS' Bridge Health Index or the sufficiency rating as found in the federally mandated National Bridge Inspection Standards. The overall purpose of this research is to investigate the concept of isolating the items that are used to make up a single rating or index in commonly used BMSs in an effort to categorize them under distinct bridge management components such as structural condition, impact on public, and hazard resistance. Each bridge management component has a defined objective as follows:

- **Structural condition component: accurately measures the structural adequacy of a bridge.**
- **Impact on public component: evaluates how bridge attributes affect the traveling public and influence bridge management.**
- **Hazard resistance component: evaluates how attributes and external factors affect the vulnerability of a bridge in regard to probability of an event as well as probability of failure.**

The specific objectives of this research are (*a*) to identify the appropriate items that make up each of the previously mentioned components and (*b*) to determine the relative importance of those items as represented by weighting factors. To achieve these objectives, two surveys were conducted seeking input from more than 40 key bridge management personnel from state departments of transportation (DOTs) and the FHWA as well as other industry professionals and experts. The first survey was used to identify the appropriate items, and the second survey was used to determine the relative importance of those items using a mathematical methodology called the analytic hierarchy process. The primary contribution of this research is to define and provide managers and decision makers with isolated bridge management components so that they can clearly recognize variations among bridges that could be overlooked when using a single rating or index. This will especially be useful for state DOTs and local agencies, such as the Wyoming DOT (from which the motivation for this research was adapted), which are developing BMSs and methods customized to their particular needs. Once the bridge management components are established (by determining the items that make up those components and their relative weights), transportation agencies may use them in a variety of ways to develop customized BMSs for complementing their asset–bridge management analysis.

BRIDGE MAINTENANCE, INSPECTION, AND MANAGEMENT

Bridge Element Deterioration and Life Expectancy in Florida and Virginia

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Most agencies having analytical capabilities in their bridge management systems use inspections based on bridge elements and condition states, and use Markovian deterioration models. It is common to base these models on expert judgment elicitation, but increasingly agencies have sufficient data to develop deterioration models using past inspection and work accomplishment data. AASHTO maintains the Pontis bridge management system, used in 45 states, and offers a standardized inspection manual. This makes it possible to estimate and compare deterioration models among agencies, to investigate the level of consistency in model parameters, and to understand how agency characteristics, policies, and climate can affect deterioration rates. In this paper, models developed for Florida and Virginia are compared, describing how the similarities and differences between these two agencies affect deterioration rates for pure Markovian and hybrid Markovian–Weibull models.

BACKGROUND

Each of the 50 states owns and manages its own inventory of highway bridges, with an average of 12,000 bridges per state. Bridge management practices evolved independently in each state, and became quite diverse over time. The National Bridge Inspection Standards began a process of harmonizing certain management functions. This movement increased in 1997 with publication of the AASHTO Guide for Commonly Recognized (CoRe) Structural Elements (*1*).

Starting in 1992, and accelerating after publication of the CoRe Element Guide, states began implementing the Pontis bridge management system. Pontis was developed by AASHTO and has been licensed by 45 states as well as local and national governments (*2*). Pontis manages each department's structure inventory and inspection data, and provides decision support for the planning of structure preservation, improvement, and replacement activities.

Decision support in Pontis uses a set of analytical models to evaluate project and program alternatives, in order to help decision makers optimize the scope and timing of structure work. It also assists in prioritizing and scheduling work, and allocating funding, across the structure inventory. To accomplish this, Pontis contains a set of forecasting models for cost, deterioration, and action effectiveness, all of which contribute to a capability to forecast life cycle costs.

The Virginia Department of Transportation (DOT) and the Florida DOT have both implemented the most up-to-date full version of Pontis, release 4.4. Subsequent releases have been updating the system to a new web-based technology platform, and adding new predictive models. It is envisioned that both states will eventually implement the new platform and models, with the next full version currently designated by AASHTO as Pontis release 5.2. However, no release date for Pontis 5.2 has been set.

Like many states, Florida and Virginia developed their first deterioration models in 2000–2001 using an expert judgment elicitation process described in the Pontis Technical Manual (*2*, *3*). Since element inspections commenced in 1995–1997 in both states, the early models were able to make limited use of inspection data for validation. In 2009 (Florida) and 2010 (Virginia), these agencies both undertook studies to re-develop their deterioration models using inspection data. The author performed both of these studies.

The analysis reported here draws on several widely accepted concepts of bridge inspection and deterioration, used in Pontis as well as in many other bridge management systems worldwide. These are described in the following sections.

Element Inspections

Both Virginia and Florida conduct inspections on a 2-year interval, using the 106 CoRe elements specified in the AASHTO guide, plus elements of their own. Examples of CoRe elements are: concrete deck with asphalt concrete overlay, unpainted steel open girder, prestressed concrete column or pile, and elastomeric bearing.

Florida adds elements to reflect specific DOT management concerns, including precast deck panels, pile jackets, drainage systems, retaining walls, sign structures, high mast light poles, and the electrical, mechanical, and hydraulic elements of moveable bridges. The state has 149 moveable bridges, the nation's largest inventory of these structures. Florida DOT uses 151 elements in all.

The additional Virginia-specific elements include sidewalks, protected and unprotected slopes, wingwalls, mechanically stabilized earth, utilities, lighting, roadways over culverts, deck overhang soffit, stay-in-place forms, and concrete slabs covered with fill. Virginia uses 132 elements in all.

Condition of each element is described using three to five standardized condition states. Condition states in most cases describe the severity of deterioration, in a manner that can be distinguished by visual inspection. Condition states affect the feasibility of maintenance, repair, and rehabilitation treatments, deterioration rates, and costs.

The definitions of condition states are significant in deciding whether two or more elements are sufficiently similar to be combined for estimation purposes. Combining of relatively uncommon elements is important in building up enough of a population size to estimate a statistically useful model. But elements can be combined only if they have the same number of condition states and if their definitions are compatible.

Markovian Deterioration Models

Bridge deterioration in Pontis is forecast using a Markovian model. A Markovian model assumes that the probability of making a transition from one condition state to another depends only on the initial state, and not on age, past conditions, or any other information about the element. Thus, the model is expressed as a simple matrix of probabilities (Table 1).

In Table 1, the rows are condition states at the beginning of the year, and the columns are condition states 1 year later. A cross-sectional model like this is especially useful for structures whose lives can extend to 50 to 100 years or more, where a full-time series data set is not obtainable.

TABLE 1 Example Deterioration Model

From	To State 1	State 2	State 3	State 4	State 5
State 1	93.6	6.4	0.0	0.0	0.0
State 2		92.0	8.0	0.0	0.0
State 3			91.1	8.9	0.0
State 4				98.7	1.3
State 5					100.0

NOTE: All amounts in percent.

A Markovian transition probability matrix is a special type of matrix with a number of desirable properties that make it easy to process. A well-formed transition probability matrix adheres to the following rules:

- Square matrix. All transition probability matrices are square. For Pontis they must be either 3×3, 4×4, or 5×5.
- Upper right triangular. Only the main diagonal and the upper right triangle of the matrix are allowed to have non-zero values. This is another way of saying that there can be no movement from any condition state to a better state in a deterioration model.
- Non-negative. No elements of the matrix may be negative.
- Positive diagonal. Elements on the diagonal must be non-zero. In other words, there must be a non-zero possibility of an element remaining in the same condition state from one inspection to the next.
- Normalized. All rows of the matrix must separately sum to 100%. In other words, the transition probability matrix must account for all possible states and transitions of the element.
- Because of the combination of these rules, the lower right corner element must be 100%. Once an element deteriorates to the worst condition state, it stays there (until the agency takes action to improve it).

Pontis defines a notional "failure" state and uses a "failure probability" as a part of the penalty for allowing elements to remain in states of advanced deterioration. Since the current analysis doesn't address the failure probability, elements that reach the worst normal condition state are assumed to remain there.

Conditions in any future year can be predicted with a Markovian model by simple matrix multiplication. Mathematically, the matrix multiplication for Markovian prediction, when no maintenance action is taken, looks like this:

$$y_k = \sum_j x_j p_{jk} \quad \text{for all } k \tag{1}$$

where x_j is the probability of being in condition state j at the beginning of the year; y_k is the probability of being in condition state k at the end of the year; and p_{jk} is the transition probability from j to k. This computation can be repeated to extend the forecast for additional years.

It is possible to derive transition probabilities if the median number of years between transitions is known. Often this is an easier way to develop a deterioration model from expert judgment. It also provides a convenient means of computing, storing, and reporting transition

probabilities derived from historical inspection data. If it takes *t* years for 50% of a population of elements to transition from state *j* to state *k = j + 1*, and no other transitions are possible, then the 1-year transition probabilities are:

$$p_{jj} = 0.5^{(1/t)} \text{ and } p_{jk} = 1 - p_{jj} \tag{2}$$

So if it takes a median of 10.23 years to transition from state 1 to state 2, then the probabilities after 1 year are 93.4% for state 1 and 6.6% for state 2.

Change in Condition

From one inspection to the next, the condition of each element on each bridge may change. Condition is made worse by time, weather, traffic, pollution, and operating conditions such as the use of deicing chemicals. These factors promote physical and chemical processes that may increase the severity of material defects, or increase the extent of defects at any given severity level.

Counteracting this normal deterioration and its impacts, the agency applies preservation actions intended to either improve condition, or at least slow the rate of deterioration. While deterioration can be observed every year, preservation actions occur infrequently, often at intervals of 10 to 30 years or more.

In order to estimate statistical models of deterioration and action effectiveness, it is necessary to separate the effect of deterioration from the effect of agency actions. These effects are not directly measured, but must be deduced from a limited amount of information in two snapshots of condition spaced 2 years apart, plus any available evidence of agency actions that may have been performed in between the two snapshots. Figure 1 shows the problem schematically.

If an agency action occurred on the element between 2005 and 2007, then the percent of the element observed to be in state 3 in 2007 may be due to a combination of normal deterioration from states 1, 2, or 3; and the effect of agency action in improving parts of the element which may previously have been in states 3, 4, or 5.

Estimation of the deterioration model is a matter of quantifying the flows along the blue paths in Figure 1, while the effectiveness model comes from quantifying the red paths. As will be described later in this paper, the deterioration paths occur between every pair of inspections on every element of every structure. In contrast, the red paths occur only in about 9% of the inspection pairs (in the Florida data), because agency actions are relatively infrequent. The strategy pursued in this research, therefore, is as follows:

1. Identify a set of inspection pairs, in which there is reasonable confidence that no preservation activities have taken place. Estimate the deterioration model from these.
2. Identify a set of inspection pairs, in which it is likely that a preservation action took place. From the change in condition, subtract the effect of deterioration. Averaged over all similar activities, this is the action effectiveness model.

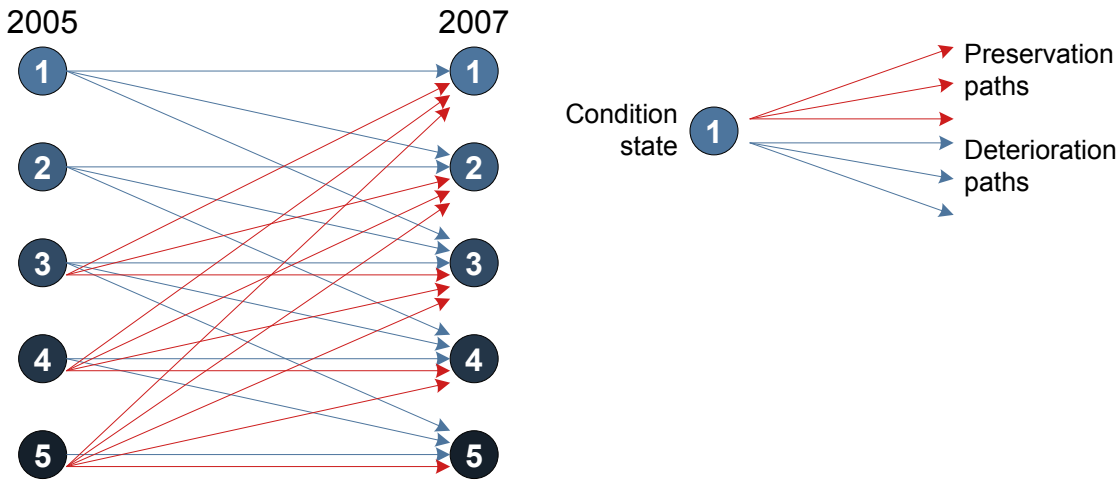

FIGURE 1 Changes in condition between inspections.

To identify inspection pairs possibly having preservation effects, a measure of condition improvement was developed, as follows:

$$CI_e = \max_{ej}\left(\sum_{k=1}^{j} y_k - \sum_{k=1}^{j} x_k\right) \tag{3}$$

where CI_e = condition improvement for element inspection pair e; j and k are condition states defined for element e; $\max_{ej}$ indicates maximization over all condition states defined for element e; y_k = fraction of the element in condition state k in the second inspection of the pair; x_k = fraction of the element in condition state k in the first inspection of the pair.

Equation 3 quantifies improvement as the increase in the fraction at, or better than, any given condition state. Computed over all condition states, the largest increase is selected to represent the inspection pair as its maximum condition improvement. Under a pure deterioration scenario where there are no preservation paths, the improvement must be non-positive for every condition state, so CI also must be non-positive (it could be zero or negative).

If any one or more of the condition states shows an increase in the fraction at its level or better, then CI is positive. This may indicate that preservation activity took place.

DATA PREPARATION

In each state, a Pontis database was provided in Sybase Adaptive Server Anywhere format. Using structured query language (SQL), the element inspections were paired in order to establish a comparison of conditions before and after a time span of 2 years (±6 months) on each element, as characterized by bridge key, element, environment, and structure unit. Inspection pairs were filtered to ensure a consistent set of data definitions and to remove questionable data. Table 2 summarizes the data sets, indicating the number of inspection pairs used in model estimation.

TABLE 2 Model Estimation Data Sets

Variable	Florida	Virginia
Structures	19,213	19,985
Years of inspection	1995–2009	1996–2010
Inspections	91,924	136,700
Element inspections	884,678	971,631
Element inspection pairs	559,311	588,813
Inspections per structure	4.8	6.8
Elements per structure	9.6	7.1
Pairs per structure	29.1	29.5

The Virginia data set included only bridges and culverts, omitting other types of structures. Florida's model included sign structures and high mast light poles in addition to bridges and culverts.

Changes in Deck Condition State Language

A particular concern in the data set is the effect of Virginia's transition, in March of 2008, from the 1997 edition of the AASHTO CoRe Element Guide, to the 2001 Interim Revisions (*1*). The revisions changed the condition state definitions of many of the deck elements and one smart flag.

In order to ensure valid results, it was necessary to partition the set of deck inspection pairs into three groups:

1. Pairs having both inspections prior to March of 2008. These data can produce valid deterioration models, but only for the old definitions.
2. Pairs having the first inspection during or before March 2008, and the second inspection during or after March of 2008. The inspection pairs would be assumed invalid because of the change in definitions that is assumed to have occurred.
3. Pairs having both inspections after March of 2008. If there is sufficient sample size, these data can produce valid deterioration models for the definitions currently used by the Virginia DOT.

All of the significant changes in deck condition state language were similar, changing the thresholds used for recognizing damaged and patched areas of the deck. Later in the analysis it was found that Group 3 had a sufficient population for estimating a deterioration model for decks as a group, but not for the 15 individual types of decks. Therefore Group 1 was used for an initial set of models, which were then scaled to current inspection standards using the models for Group 3. Florida did not undergo this change in the inspection process, so its deck condition data were comparable to Virginia's Group 1 inspection pairs.

Maintenance, Repair, and Rehabilitation Data

In the Florida study, the analysis benefited from availability of databases of bridge maintenance, repair, and rehabilitation activities for the entire timeframe of the analysis. These data records in

most cases identified the bridge that received the activity, but they offered only a very coarse coding of the type of activity, which did not identify the elements that were repaired. Most records did have a textual description of the work, however.

To make use of the work accomplishment data, each record was processed using several steps:

- Based on work date, the record was associated with element inspections before and after it.
- Work descriptions were parsed using a dictionary of key words, to estimate the probability that the record would fall into each of the action types recognized in Pontis.
- Using the coarse maintenance activity codes, the text parsing results, the element composition of the bridge, and the identification of specific improvements in element condition, each record was associated with the most likely elements and condition states to which it was applied, and was associated with a specific Pontis action type.

This information on estimated work activity helped in developing a strategy for filtering preservation paths out of the inspection pairs for the deterioration model. It also formed the basis for estimating the action effectiveness model.

Virginia DOT did not have any usable work accomplishment data, so information on action types was unavailable. This was found to make a significant difference in the acceptability of the deterioration results, and limited the usefulness of action effectiveness models.

ESTIMATING THE MARKOV MODEL

A set of models was developed for each element where possible, and also for groups of elements as described below. Each model was expressed as a vector of transition probabilities, and was also converted to an equivalent estimate of the median transition time between states, using the inverse of Equation 2:

$$t = \frac{\log(0.5)}{\log(p_{jj})} \tag{4}$$

To aid in model evaluation, each matrix was further condensed by calculating the median life expectancy. This is the median number of years for an element starting in perfect condition, to deteriorate to a point where 50% has reached the worst defined condition state, based on iterative forecasting using Equation 1.

Model Estimation Method

Pontis contains a linear regression procedure that can be used to estimate Markovian deterioration models from inspection data. Research in Florida (*4*) found that the regression method can be simplified by taking advantage of the typical 2-year inspection period and 1-year transition period. Since bridges deteriorate slowly, not much happens in such a short time. If p_{13} and all other elements non-adjacent to the diagonal are assumed to be zero, as in Table 1, then it

is a one-step transition matrix. The Florida research found that such a matrix can be estimated with far fewer data points and does not sacrifice any significant explanatory power.

To set up the estimation of a one-step matrix, the prediction equation is defined as follows:

$$\begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \end{bmatrix} = \begin{bmatrix} p_{11} & p_{12} & 0 & 0 \\ & p_{22} & p_{23} & 0 \\ & & p_{33} & p_{34} \\ & & & p_{44} \end{bmatrix}^2 \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} \tag{5}$$

The element inspection vectors [Y] and [X] are spaced 2 years apart, but the transition probability matrix [P] is expressed for a 1-year transition. Hence, it is applied twice. Writing out the individual equations necessary to calculate [Y] results in:

$$\begin{aligned} y_1 &= x_1 p_{11} p_{11} \\ y_2 &= x_1 p_{11} p_{12} + x_1 p_{12} p_{22} + x_2 p_{22} p_{22} \\ y_3 &= x_1 p_{12} p_{23} + x_2 p_{22} p_{23} + x_2 p_{23} p_{33} + x_3 p_{33} p_{33} \\ y_4 &= x_2 p_{23} p_{34} + x_3 p_{33} p_{34} + x_3 p_{34} p_{44} + x_4 p_{44} p_{44} \end{aligned} \tag{6}$$

Since the sum of each row in [P] must be 1.0, the following additional equations apply:

$$p_{12} = 1 - p_{11} \qquad p_{23} = 1 - p_{22} \qquad p_{34} = 1 - p_{33} \tag{7}$$

The vectors [X] and [Y] can be computed from the database of inspection pairs to describe the combined condition of the element before and after. So these quantities are known. Thus the system of seven equations and seven unknowns can be solved algebraically for the elements of [P]. First find p_{11} from Equation 6, then find p_{12} from Equation 7, then p_{22} and p_{23}, and so on in a simple sequence.

A complication arises because the equations are second-order polynomials in p_{ii}, so it is necessary to use the quadratic equation to find the roots. For example, the equation for p_{33} is:

$$\begin{aligned} p_{33} &= \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \\ a &= x_3 \qquad b = x_2 p_{23} \qquad c = x_1 p_{12} p_{23} + x_2 p_{22} p_{23} - y_3 \end{aligned} \tag{8}$$

The same pattern of equations and solution methods apply to elements having three or five condition states as well. Each same-state transition probability p_{ii} is constrained to be in the range from 0 to 1 exclusive. Even though the quadratic equation finds two roots, in practice only zero or one root are in the necessary range. Out of the 755 models in Florida, only four had zero roots and none had more than one root. Virginia had similar results using the same method.

The model estimation and evaluation process was automated using Microsoft Excel and Visual Basic for Applications.

Model Refinement

In both Florida and Virginia, fewer than half of the elements produced usable models when all elements were modeled separately. The rest of the elements were too uncommon to present a clear progression of deterioration through all possible condition states.

In order to generate a more complete set of models, the individual element models were grouped, and their data sets pooled. This was done by collapsing similar elements into element types. The elements within each new element type share the following characteristics:

- The same number of condition states with the same or similar definitions.
- Similar transition times, or good intuitive reason to expect that they would be similar (e.g., similar materials and exposure).
- When combined, a sufficient sample size to expect a usable model. The earlier Florida research (*4*) found that, as a rule of thumb, at least 500 inspection pairs are required in order to achieve a usable model.
- Elements were not combined with others if they had significant sample sizes and reasonable results on their own.

Element grouping was an iterative process, where it was necessary to investigate and compare alternative grouping schemes in order to find the one that gave the most complete and consistent results. This process resulted in somewhat different groupings in Virginia and Florida. Table 3 shows a comparison of comparable element types for the two agencies, and also shows typical results for Florida elements that were not present in the Virginia data set.

Both sets of models exhibited consistently high values of the coefficient of determination. In Florida the average R^2 value was 0.73 while in Virginia it was 0.83.

Florida DOT performed a comparison between its original 2001 expert judgment models, and its new models based on inspection data (*4*). The analysis found that true element life expectancy (from inspection data) was nearly twice as long as suggested by the expert elicitation models. The Virginia analysis confirms this result, with true historical life expectancy 2.1 times as long, on average, as the corresponding results of the earlier expert elicitation process. This serves to emphasize the importance of developing models based on actual inspection data as soon as possible in the implementation of a bridge management system.

Discussion

Concrete elements were found to have especially long life spans in both models, especially in Virginia. In fact, the average life expectancy over all element types was found to be 33% longer in Virginia than in Florida. This difference also was evident in the 2001 expert elicitation models developed in both states. It may be due to the differing nature of structures in the two states' inventories. The average traffic volume on a bridge in the Virginia inventory is 8,152 vehicles per day, while in the Florida inventory the average volume is 17,666. To further explore the effect of traffic volume, the Virginia study estimated separate sets of models for the various districts and functional classes in the state. Those with higher traffic volume consistently showed faster deterioration across nearly all types of elements.

TABLE 3 Comparison of Florida and Virginia Results (median years to make each indicated state transition)

	Florida					Virginia					VA/FL
Element Type	**1-2**	**2-3**	**3-4**	**4-5**	**1-5**	**1-2**	**2-3**	**3-4**	**4-5**	**1-5**	**Ratio**
Concrete or steel deck/slab	5	41	21	22	114	7	10	6	8	44	0.39
Timber deck/slab	5	12	15		41	31	21			139	3.38
Approach slab	12	25	28		83	17	35	143	2	225	2.70
Strip seal expansion joint	13	45			67	17	14			39	0.58
Pourable joint seal	10	8			23	13	8			27	1.17
Compression joint seal	6	11			21	19	16			43	2.05
Assembly joint/seal	14	14			34	27	36			77	2.26
Open expansion joint	18	30			58	35	48			102	1.76
Uncoated metal railing	74	5			84	27	29	12		87	1.04
Coated metal railing	18	10	4	2	45	40	20	25	19	138	3.07
Reinforced concrete railing	68	24	38		163	56	53	50		207	1.27
Timber railing	12	9			26	48	10			64	2.46
Other railing	37	16			62	71	42			135	2.18
Unpainted steel super/substructure	13	9	13		46	27	32	36		123	2.67
Painted steel girders/floor beams	10	8	8	57	99	20	11	16	17	87	0.87
Painted steel stringers	10	17	5	275	323	26	12	17	17	97	0.30
Painted steel truss: bottom chord	13	5	13	7	51	16	8	17	21	84	1.65
Painted steel truss: top or arch	7	5	11	152	189	25	13	15	13	89	0.47
Pre-stressed concrete superstructure	293	13	14		335	32	13	16		78	0.23
Reinforced concrete superstructure	32	9	21		80	67	29	92		237	2.96
Timber superstructure	41	27	6		92	57	17	28		128	1.39
Elastomeric bearing	96	242			393	48	113			188	0.48
Metal bearing	14	48			72	39	68			119	1.65
Painted steel substructure	8	7	2	5	32	14	6	6	39	82	2.56
Concrete column/pile	28	17	99		171	51	25	157		274	1.60
Concrete abutment	87	15	496		656	68	58	146		341	0.52
Concrete cap	145	9	199		428	68	11	164		287	0.67
Pile cap/footing	9	14	79		116	24	20	104		174	1.50
Timber substructure	24	18	5		58	36	19	30		110	1.90
Reinforced concrete culvert	7	37	138		208	62	78	102		312	1.50
Metal/other culvert	8	29	34		91	16	20	17		69	0.76
Pile jacket w/o cathodic protection	13	17	18		63						
Pile jacket with cathodic protection	19	56	43		150						
Fender/dolphin/bulkhead/seawall	11	9	27		60						
Slope protection	51	14	53		143	21	12	38		89	0.62
Drainage system	7	3	2	1	17						
Metal retaining wall	9	6	71		95	30	14	15		77	0.81
Concrete retaining wall	50	11	66		158	66	36	67		216	1.37
Timber retaining wall	24	9	14		61	35	13	29		98	1.61
Sign structures/high-mast light poles	13	13	7	28	75						
Moveable bridge mechanical	8	19	12	1	49						
Moveable bridge hydraulic	7	11	10		37						
Moveable bridge electrical	18	11	2		37						

Even considering the effect of traffic volume, some of the Virginia transition times appear to be unreasonably long. This is especially an issue with reinforced concrete, and is especially prevalent in the transition into the worst defined condition state. This issue was

discussed at length with a Virginia DOT expert panel. In the context of discussing the results for specific elements, the following potential causes were identified:

1. In the absence of hard data on maintenance work accomplishments, it is likely that many bridge elements are receiving unknown maintenance actions. The procedures to filter inspections can only detect conditions that improve between inspections; they do not detect actions that may have occurred that caused conditions to stay the same (i.e., prevented further deterioration but did not improve condition).
2. Certain elements and materials, particularly weathering steel and prestressed concrete, may occur primarily on newer bridges. The Markovian analysis ignores age effects, and might be biased by the relatively new population. Analyses conducted by other agencies, such as Florida, have shown that there is a significant age dependency in the onset of deterioration.
3. Since inspection data had not been used for this purpose in Virginia DOT in the past, it is possible that the procedures used in the field by inspectors are not picking up significant deterioration factors that would affect a maintenance-oriented deterioration analysis such as is done in Pontis. Traditionally the emphasis in bridge inspection has been on identifying immediate needs affecting bridge functionality and safety, rather than preventive maintenance.
4. Related to issue 3, the condition state language in some cases describes specific defects that are very uncommon in practice. For example, imminent loss of bearing is very uncommon, as is the need for structural analysis. Inspectors might be reluctant to assign a condition state that describes such an uncommon defect, unless that specific defect is actually present. Thus, it is possible that less dramatic defects that correspond to the same condition state might go unrecorded.

In connection with issue 1, it is important to be clear on the types of actions that should and should not be ignored. Pontis is used for identifying programmed, condition-responsive preservation actions. It does not identify interval-based actions, which include a wide variety of preventive maintenance and minor repair actions. The expert panel noted that minor timber repairs are an especially good example of this type of maintenance, since they can be done to a timber bridge element in any condition state. It is likely that this is also the case with concrete. Joint cleaning and gland repair may also be good examples. In the absence of any filtering for preservation activity, the deterioration model describes the total effects of current maintenance policy, which includes life extension of elements.

For the Pontis models to be used in the most accurate way possible, the do-nothing deterioration model should include the effects of all activities that Pontis does not specifically identify, and should exclude all activities that are specifically analyzed in Pontis. In general that means the do-nothing model should include the effects of interval-based maintenance (or routine maintenance) and should exclude programmed maintenance, repair, and rehabilitation.

What this means for issue 1 is that it is not a problem if interval-based maintenance is unknown and unfiltered. In many cases, long transition times may simply mean that routine maintenance is being performed and is effective in delaying further deterioration. The Pontis analysis will be inaccurate if this routine maintenance is intentionally left out of the deterioration model. However, the improvement of Virginia's deterioration models in the long term will require a systematic process for recording programmed maintenance activity. Steps have already been taken toward implementation of such a process.

Issue 2 was corrected in the study by use of a Weibull model of the onset of deterioration, described below. The model was formulated to jointly estimate both the transition time and shaping parameter of the model. As expected, the analysis led to a shorter median transition time from condition state 1 to state 2.

Issues 3 and 4 probably cannot be corrected by analyzing current data, but may require an assessment of the bridge inspection process, to ensure that inspectors are recording defects related to maintenance needs, and not just to safety and functionality concerns. Other states have also noted that this can be an issue with the element inspection process and have worked with their inspectors to improve the recording of all relevant defects.

ONSET OF DETERIORATION

The Florida and Virginia studies both went on to estimate Weibull models of the onset of deterioration. Instead of assuming a constant transition probability from new condition to state 2, the Weibull model allows the probability to vary with age (*4*). The Weibull curve has the following functional form:

$$y_{1g} = \exp\left(-\left(g/\alpha\right)^{\beta}\right) \tag{9}$$

where y_{1g} is the state probability of condition state 1 at age (year) g, if no intervening maintenance action is taken between year 0 and year g; β is the shaping parameter, which determines the initial slowing effect on deterioration; and α is the scaling parameter, calculated as:

$$\alpha = \frac{t}{(\ln 2)^{1/\beta}} \tag{10}$$

where t is the median transition time from state 1 to state 2, which can come from the Markov model as estimated above, or can be estimated jointly with β.

Table 4 compares the β values in Florida and Virginia. It can be seen that the onset of deterioration is significantly slower in Virginia than in Florida. This difference is unlikely to be explained by maintenance activity, routine maintenance policies, or unrecorded defects. The climatic differences between the two states would be expected to produce faster, not slower deterioration in Virginia. It is more likely to be a result of differences in traffic volume.

CONCLUSIONS

Figure 2 compares a few common elements in the Virginia results, using a hybrid deterioration model that combines Markov transition probabilities with the Weibull model of onset of deterioration. The curves are expressed in the form of health index (*5*) to make the trends easy to see.

The Virginia study confirmed the Florida conclusions that the one-step method of estimating transition probabilities produces results statistically comparable to the Pontis

TABLE 4 Comparison of Shaping Parameters

Group name	Florida	Virginia
Concrete deck/slab	1.3	2.4
Approach slab	1.0	2.1
Simple expansion joint	1.0	1.5
Complex expansion joint	1.4	3.1
Uncoated steel	1.1	2.7
Coated steel	1.8	3.1
Reinforced concrete	2.0	1.9
Pre-stressed concrete		4.3
Timber above ground	1.9	2.2
Timber in ground	3.5	2.7
Other material (asphalt, masonry)	2.5	4.0
Bearing	1.9	3.5
Sign structures and poles	1.0	
Moveable bridge mechanical	1.6	
Moveable bridge structure	4.1	
Moveable bridge electrical	3.0	
Moveable bridge other	1.1	

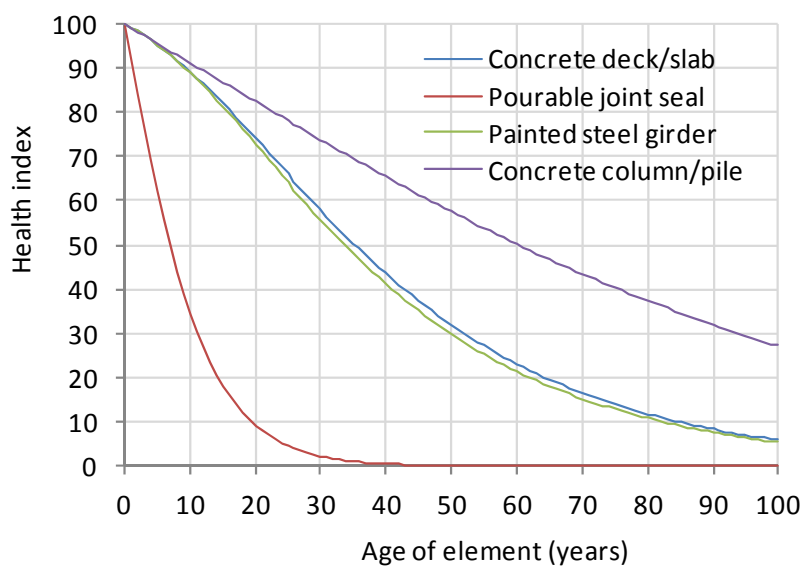

FIGURE 2 Comparison of some common elements in Virginia.

regression-based approach, using smaller sets of data. It also confirmed the value of the Weibull onset model to improve the predictive power of the deterioration model.

In both studies, transition times and life expectancy were found to be twice as long as the results determined earlier from expert judgment. This serves to emphasize the importance of developing models based on actual inspection data as soon as possible in the implementation of a bridge management system.

The availability of maintenance work accomplishment data in the Florida study was found to significantly enhance the reasonableness of the analysis results, in comparison to the Virginia results. Such data would greatly improve the understanding of differences in deterioration rates between populations of structures.

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BRIDGE MAINTENANCE, INSPECTION, AND MANAGEMENT

Minnesota Department of Transportation's New Integrated Bridge Maintenance, Inspection, and Management System

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The Minnesota Department of Transportation (DOT) oversees 21,000 bridges and culverts 10 ft and over. For all structures, Pontis and structural inventory and appraisal data are collected during regular inspections along with detailed maintenance information managed by district personnel. Minnesota DOT had previously used a combination of decentralized databases for managing its bridges. The department recognized that the ability existed to improve the inspection, management, and maintenance process via an integrated software system and process. Minnesota DOT launched a project to develop its Structure Information Management System, which now allows for unified entry and management of all statewide bridge and culvert data. The new system improves the transfer of data between the central office and districts while providing a number of tools for overall improvement of the maintenance process. For improving inspections, the software allows for entry of data on the condition and maintenance needs in the field using tablet or laptop computers as well as an integrated internet module for continuing reports and reviewing data. Minnesota DOT users, private consultants, and local entities are able to use the system according to their permissions. Multiple personnel on fracture critical inspection teams can also simultaneously collect information on different parts of the bridges and merge the data together into a single report on the server. The system also manages the hundreds of pictures and other digital resources taken on large bridges and directly links to appropriate location (bearing, pier, or other component). An especially useful feature is the ability to integrate all bridge maintenance activities with all bridge inspection and management data. All state and district maintenance personnel are able to plan, enter, and record all maintenance activities via the software. Some of the in-depth management features include the ability to automatically spot trends occurring, quantify maintenance needs and priorities, and use an advanced scheduling module. The software allows for access to the data from multiple sites via secure web interfaces. Limited access can also be provided to other interested parties such as maintenance and capital planning divisions, allowing for seamless sharing and updating of planned activities. For improving the maintenance and management process, Minnesota DOT personnel also use interactive maps, full querying, dashboards, trending tools, and customized reports to best prioritize their maintenance activities. The state's experience moving to an integrated electronic program will be highlighted. This presentation would provide a real-world example of how a state made the transition to a new software system for its bridge inspection and maintenance needs. Many other bridge owners and inspectors face similar problems and would benefit from the lessons learned in this project.

BRIDGE MAINTENANCE, INSPECTION, AND MANAGEMENT

Effective Use of Structural Health Monitoring for Highway Bridge Maintenance

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The Oregon Department of Transportation began implementation of structural health monitoring (SHM) in 2000. Currently, 13 highway bridges have permanent SHM systems installed that monitor various performance parameters and log the data onto a central computer server that allows engineers to access both historic and real-time responses from their desks on the state's computer network. The primary goal of this program is to better understand and resolve specific problems or deficiencies with specific components or portions of the bridges. Examples of such applications include foundation stability, steel fatigue, movable bridge machinery, cathodic protection, wind-induced vibration, and diagonal tension cracks in reinforced concrete. For each SHM system design, physical performance parameters that can be either qualitatively or quantitatively related to the deficiency were identified and measurement methods developed to be monitored. Data from these measurements are used to estimate current condition or serviceability, develop appropriate repair or retrofit designs, and allow predictions of remaining service life. In this presentation, a brief summary of the purpose and taxonomy of SHM will be presented. Both qualitative and quantitative measurement parameters as they apply to highway bridges will be discussed. Specific examples will be discussed about each type of measurement parameter ranging from qualitative measurements such as acoustic emission to quantitative measurement parameters such as strain, which is used to calculate real time reliability factors for both specific components and the structure as a whole. An outline of the SHM design process will also be discussed, with emphasis on systems that provide practical and meaningful information for highway bridge maintenance engineers.

The objective of this paper is to provide an introduction to structural health monitoring (SHM) for bridge owners and their representatives who are interested in its practical uses and implementations on highway bridges. A brief discussion is provided of the current terminology, classifications, and methodologies used in SHM and similar disciplines, followed by examples of implementations on Oregon Department of Transportation's (DOT's) bridge inventory. This paper is intended to be a brief overview; all cited references should be consulted for more detailed and thorough descriptions of the various definitions and methods presented.

TERMINOLOGY

SHM has different meanings depending on the venue and context in which it is being discussed. From a non-specific view it is often thought to be an online or real-time condition or performance monitoring system that measures, logs, and possibly analyzes data from sensors. The measurements are generally used to characterize both the demands on the structure, such as

forces or changes in temperature, and the response of the structure to these demands. Basic monitoring of the demands and responses are best described as structural performance or usage monitoring (*1*). Over the last few decades SHM has been developing into condition assessment or damage identification monitoring.

The vernacular definition of SHM is "the process of implementing a damage identification strategy for aerospace, civil and mechanical engineering infrastructure" (*2–4*).

Damages of common concern on bridges include corrosion and resulting section loss, fatigue and resulting cracking, displacements at supports, and resulting loss of connectivity, etc. As present by (*5*), damage can be defined as a state when the structure is longer operating in its ideal condition. As damage accumulates it can lead to a fault which is defined as the state when the structure can no longer operate in a satisfactory manner. Ideally the outcome of damage identification (SHM) is to prevent faults from occurring by implementing condition-based maintenance strategies before the damage develops into faults.

Rytter (*6*) and then Worden et al. (*5*) describe the damage identification process in a hierarchical structure as follows:

- Detection gives a qualitative indication that damage might be present in the structure.
- Localization gives information about the probable position of the damage.
- Classification gives information about the type of damage.
- Assessment gives an estimate of the extent of the damage.
- Prediction gives information about the safety or estimates of remaining life.

Ideally, all five of these components could be accomplished in an online and automated manner. Efforts employing statistical pattern recognition using supervised and unsupervised learning approaches are developing at this time (*1*, *5*, *7*). However, portions or entireties of each component are not currently at a stage of maturity where they are likely to be fully automated with respect to applications on the highway bridges.

There are four other disciplines that are closely related to or part of SHM. These are (1) condition monitoring (CM) which is an application of SHM specific to rotating machinery; (2) statistical process control which is applied to processes; (3) nondestructive evaluation which is offline, component specific damage characterization; and (4) damage prognosis which is the prediction of remaining life. Developments within each of these individual disciplines often benefit or advance the others. As a result, it is likely that more practical automation of the five components of damage identification in bridge structures will be available in the near future.

FUNDAMENTAL AXIOMS OF SHM

It is important to first present the fundamental axioms or truths of SHM as observed by Worden et al. (*4*) before discussing the practical implementation of SHM to highway bridges. Understanding of these truisms will greatly improve the implementation of SHM if they are properly considered into the design and operation of the system.

Axiom I: All materials have inherent flaws or defects.

Axiom II: The assessment of damage requires a comparison between two system states.

Axiom III: Identifying the existence and location of damage can be done in an unsupervised mode, but identifying the type of damage present and the damage severity can generally only be done in a supervised learning mode.

Axiom IVa: Sensors cannot measure existing damage. Feature extraction through signal processing and statistical classification is necessary to convert sensor data to information on damage.

Axiom IVb: Without intelligent feature extraction, the more sensitive a measurement is to damage, the more sensitive it is to changing operational and environmental conditions.

Axiom V: The length and time scales associated with damage initiation and its evolution dictates the required properties of the SHM sensing system.

Axiom VI: There is a trade-off between the sensitivity to damage of an algorithm and its noise rejection capability.

Axiom VII: The size of damage that can be detected from changes in system dynamics is inversely proportional to the frequency range of excitation.

The cited reference provides a detailed discussion of each of these truisms. A good understanding of these can be very useful in evaluating various approaches and implementations of SHM. It is also useful in identifying questionable or false claims of system capabilities when a bridge owner representative is considering various systems on the market or to be designed for a specific structure.

PRACTICAL APPLICATION OF SHM FOR HIGHWAY BRIDGES

Overview

What can be practically implemented with the current discipline maturity and technical development to provide for more efficient and reliable operation of bridge structures? As previously discussed, automation of all five components of damage identification is not practical at this time. However, online automated monitoring is useful for completing some of these components. The following is a discussion of the practical and reliable applications to highway bridges for each of the components.

Detection

The detection of damage in a bridge structure is most often accomplished using time-based visual inspection methods. This is a practical and usually successful approach, even though it is not online or automated. Research is being conducted on automating this component using statistical pattern recognition approaches. Currently the authors do not believe the technology has developed adequately in the application to highway bridges to warrant consideration of automating this component. Both technological and legal impediments will likely prevent the full automation of this component for some time.

Localization

At this time the localization of damage in bridge structures is also mostly reliant on visual inspection methods. Opportunities for partial automation of this component do currently exist in some applications. One example is structural performance monitoring that provides information on changes in connectivity and structural stiffness on a spatially global basis. This is accomplished using curvature and vibration analysis approaches. Both pattern recognition and inverse methods are developing approaches that can be used in automating this component. In the future it is likely that an increasing number of practical and reliable applications will be available.

Classification

The classification of damage is typically accomplished using standard nondestructive testing (NDT) methods such as visual testing, magnetic particle testing, ultrasonic testing, and half-cell corrosion surveys to cite just a few. They are applied to specific components of the structure in a manual offline manner. Again, statistical pattern recognition methods are being used to develop automated applications for this component.

Assessment

The assessment of the extent of damage is also commonly accomplished using manual NDT methods. Opportunities in some applications to supplement this component with online automated methods do exist. These methods of monitoring the progression of known damage are becoming more common, robust and practical. A few examples include fatigue crack growth, corrosion activity, and scour of foundations.

Prediction

The prognosis or prediction component of SHM likely has the most useful and practical applications available to the highway bridge owner at this time. This component is useful for remaining life estimates for structures with both known and unknown states of damage. For specific forms of known damage such as corrosion or fatigue cracking, online monitoring can be practically employed to develop remaining life estimates. For unknown damage states, the probability of developing damage and faults can be estimated in an on-line automated manner. The results of the prognosis component of SHM can be used to tailor inspection and maintenance intervals and quantify the level of risk of a fault occurring under current demands, condition, and use.

Applications on Oregon DOT Bridges

The Oregon DOT's approach to developing a SHM program began with implementation of basic structural performance monitoring applied to highway bridges with known defects or deficiencies. Systems were designed and installed that quantify the basic causes and effects of the particular damage or deficiency identified from conventional inspection and analysis methods. Sensor threshold crossing approaches were used to trigger data logging, and data

analyses were performed offline. In most cases the results were used to assess the severity of the damage, evaluate the effectiveness of repairs, and, in one special case, provided an automated warning notification of a significant change in condition. As the SHM program has grown and developed, Oregon DOT is investigating applications with increased sophistication and automation that can accomplish the prediction component of SHM. Some of these Oregon DOT bridge SHM applications are briefly discussed below.

Foundation Monitoring

The first application began in 2000 with the Isthmus Slough bascule movable bridge in Coos Bay, Oregon. One of the bascule piers would move occasionally such that the bascule leaves would bind and not properly open or close for marine traffic. A geotechnical investigation was performed followed by a major maintenance contract on the long approach spans that were believed to be adversely affecting the bascule pier. The demand parameters measured were temperature and tide elevation. The response parameters were pier tilt and hydraulic pressure in the span locking mechanisms. The monitoring data has shown that the repairs have corrected the deficiency.

Another application of foundation monitoring is the Spencer Creek Bridge located on US-101 near Lincoln City, Oregon. This bridge was constructed in 2006 using a structure type not well suited for the local soil conditions. A SHM system was designed and installed during construction to monitor the performance of the deck arch anchorages. Rainfall and temperature are monitored to characterize changes in loading conditions, soil pressure, structural displacements and rotations are monitored to characterize the structural response.

A third application is a large four-span concrete deck girder bridge that was constructed on US-20 near Eddyville, Oregon, in 2009 as part of a 7-mi highway realignment project. The excavation and fill required for the realignment triggered movements in an ancient landslide that has put the completed bridge structure at risk of severe damage due to the ground movements. Temperature, rainfall, soil movement, and soil pressure are measured to capture changes in demand while concrete surface strain, column tilt, and expansion joint motions are measured to capture the structural response. Information from the system data will be used to facilitate the decision of whether or not to continue with the full realignment project and open the highway to vehicle traffic. If the project does continue, the structural performance monitoring system will be reconfigured to include automated warning capabilities. Triggering of the warning notification will likely be based on a simple sensor threshold crossing approach as was used on the Isthmus Slough bridge system.

Movable Bridges

Oregon DOT has 13 movable bridges, three of which have SHM systems installed. A pair of 240-ft span vertical lift bridges carries I-5 over the Columbia River connecting Portland, Oregon, and Vancouver, Washington. Periodic tilting of the 2.3-million-pound concrete counterweights was causing both operational and public safety concerns. A monitoring system was designed and installed to quantify the tilting of the counterweights over time and the basic lift span drive performance. The data from this system has provided accurate feedback to make periodic adjustments of the movable ballast on each counterweight. Additionally, the monitoring data is used to design and plan additional adjustments as required, assess the current state of mass

balance between the counterweights and lift span, and to monitor friction levels in the drive machinery.

The Umpqua river bridge is a 430-ft swing span carrying US-101 near Reedsport, Oregon. In 2006 significant noise and structural vibrations would occasionally emanate from the center pivot bearing during opening and closing for marine traffic. The fault in the bearing was found to be caused by a lack of lubrication. The bearing lenses of the center pivot were re-machined to restore a proper finish and were then put back into service. A SHM system was designed and installed to monitor the span drive performance during operation. Motor torque and span kinematics are the primary features measured along with ambient conditions of wind and temperature. The data are used to monitor friction levels in the center bearing. Additionally the system provides a logging feature to document usage of the moveable bridge. Movable bridge drive machinery is a potential application that can include many if not all of the damage identification components in an automated SHM system due to the progresses made in CM as previously cited.

Concrete Bridge Superstructures

Two concrete bridge superstructures in Oregon DOT's inventory have received SHM systems: the Luckiamute River Bridge and the Banzer Bridge. Both structures have developed significant diagonal tension and flexure cracking in the concrete girders from increasing service loads. Load rating analyses have demonstrated acceptable strength. The SHM systems on these structures monitor crack opening displacements and reinforcing steel strains in both shear and flexural sections of the girders. Crack opening width was found to be a reasonable qualitative indicator of accumulative damage in conventionally reinforced girders (*8*), and the strain cycle history on the reinforcing steel can be used for remaining fatigue life evaluation.

Steel Bridge Superstructures

Two steel bridge superstructures in Oregon DOT's inventory have SHM systems. These include the Fremont Bridge spanning the Willamette River in Portland, Oregon, and Kamal's Bridge which connects I-5 and I-205 in Tualatin, Oregon. Strain gages installed on the box girders at multiple sections along the spans monitor global structural strains in response to live loads. Additionally the Fremont Bridge monitors thermal strains and hot-spot strains at particular fatigue prone details. Both transient time histories and rain-flow cycle counting data are collected. The monitoring data is used for both remaining life estimates and prioritizing fatigue detail retrofitting projects.

Monitoring Bridges Without Known Deficiencies

All of the applications discussed above involve highway bridges with known defects or deficiencies. For all of these SHM systems, the measured data is used to assist the analysis of the prediction or remaining life component concerning the known damages. Thus, other than the actual data collection, all of the damage identification components are performed offline with the exception of a few systems where simple sensor threshold crossings are very meaningful.

The Quartz Creek Bridge is a multispan steel deck girder bridge supported on tall riveted towers. Quartz Creek is unique because it's SHM system has been designed for a bridge that

does not have any significant known deficiencies or defects other than a modest, though acceptable, structural load capacity rating. Spans are simple with pin and hanger joints. Designed in 1937 to HS15 loads, it will need to carry modern loads for many years to come as it is on an important route. The objective of the SHM system is to develop online real-time estimates of the operational structural reliability factor β, as defined in the load and resistance factor ratings. This information will be useful for calibrating the load rating process by providing real operational indicators of reliability. Service loads are expected to increase in magnitude and frequency of occurrence in the future and the data can be used to optimize future maintenance and strengthening retrofits.

Methodologies for monitoring and online prognosis of the reliability of in-service steel bridge superstructures have been presented in recent publications (*9*, *10*). The Quartz Creek Bridge offers a unique opportunity to employ these methods. The geometry of the superstructure contains simple spans connected with pin and hanger assemblies and the discrete vertical support at the towers will allow for a practical and reliable means of quantifying the live loading or demand distribution in real time. This bridge was recently retrofitted to increase capacity. Materials from pins, hangers, and other structural steel components were replaced which will allow for a robust testing program on the critical elements and thus provide reasonable estimates of the resistance distribution. The existing condition or state of damage was quantified using conventional offline NDT methods. With the demand and resistance distributions quantified, the reliability index for both strength and fatigue can be estimated and logged in real time.

CONCLUSIONS

SHM has developed into a damage identification process that should be used on structures for health or condition monitoring in an online, automated manner. This can provide real-time information that can be used to improve reliability and possibly improve the effectiveness of funding spent for operation by progressing from a time based maintenance philosophy to a condition-based maintenance philosophy. With the current state of the art, the most practical applications of online automated SHM for highway bridge owners is fundamentally performance monitoring with options in prognosis of the serviceability at the current damage condition.

Historically, major changes in bridge design and maintenance strategies are very slow to occur and require significant experience and proven results before being adapted. The authors believe that the state of the art of SHM and the development in hardware and analysis methods are sufficiently advanced. Bridge owners should begin to consider applying some or all of the components or concepts of SHM to highway bridges. In its simplest form, gaining experience and comfort with basic structural performance monitoring is a worthwhile endeavor. This experience is also a necessary prerequisite for implementing more-involved SHM systems that are beneficial for optimizing the maintenance and ownership of highway bridges.

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BRIDGE MAINTENANCE, INSPECTION, AND MANAGEMENT

Bridge Deck Preservation and Crash Reduction

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With nearly 600,000 road bridges in the United States that serve every community in the nation, these vital structures are a critical element in commerce and national security. They transit goods and people to market and represent an investment on a colossal scale for the country. With this prized asset it would be accepted that an ongoing and continuous program would be in place to ensure the good health of such an investment; this unfortunately is not always the case, because many counties' bridge decks are classified as structurally deficient. Various maintenance efforts have been focused on the preservation of the bridges' running surface, the "bridge deck." These efforts have spawned multiple material manufacturers who supply a variety of sealers and other products to extend the life cycle of bridge decks. While maintaining and extending the working life of these bridge decks is important, the type of deck and its location also play an important role in the choice of treatment to be used. With the availability of state-of-the-art automated application equipment and the use of high-friction surfacing in the battle to add years onto the nations bridges, this has allowed highway agencies to program maintenance of their bridge decks in limited time windows to lessen the cost of traffic management and inconvenience to the driving public. With the addition of high-friction surfacing on bridge decks that have horizontal curves, a safety component is added at the same time to reduce skid-off-the-road crashes and save lives.

Maintenance of Roadways and Roadsides

MAINTENANCE OF ROADWAYS AND ROADSIDES

Level of Service Ranking Using the Percent-Within-Limits Measure

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A highway maintenance management system has many facets, with the primary purpose of discovering and applying the safest and most cost-effective repair strategies to serve the needs of the motoring public. A prerequisite for such a system is a means of analyzing existing conditions in order to judge which components are in greatest need of treatment, and which might be the most cost beneficial to receive treatment. The purpose of this paper is to illustrate a statistically based procedure using the level-of-service (LOS) and percent-within-limits (PWL) measures to assist in highway maintenance management decisions. LOS and PWL are two of the most widely used measures in their respective fields of maintenance management and highway quality assurance. PWL has gained wide acceptance in recent years because it provides an efficient way to account for both central tendency and variability, both of which typically affect performance. Actual LOS data from a state were sampled to identify those segments in greatest need of maintenance, based upon a minimum acceptable LOS = 80 and PWL score. Data from one transportation district found two of five counties had mean LOS for three functional classes at or below 80. An analysis of 142 highway segments in one county measured a mean LOS of 85.1, suggesting that an acceptable quality level is being achieved; however, computation of the PWL identified that only 79.7% of those highway segments were in compliance. Finally, a cost-based approach is presented for ranking and determining maintenance strategies of deficient segments.

In recent years, transportation maintenance quality assurance (MQA) programs have been developed to assure that maintenance quality is being achieved. MQA programs are designed to detect insufficient maintenance efforts, poor material performance, and incorrect procedures when evaluating end-product performance. In light of these efforts, a 2011 report by the Pew Center on the States and the Rockefeller Foundation identified that while certain states have the essential tools in place to make more cost-effective transportation funding and policy choices, many trail behind by lacking a full array of tools needed to account for the return on investment in their transportation systems (*1*).

A recent paper by Weed et al. (*2*) described a new ranking procedure based on statistical measures widely used in the quality assurance field. It applied the technique of confidence interval estimation to provide a sequential list ordered by pavement condition, and is well suited to present a graphical snapshot of system condition. The purpose of this paper is to expand development of confidence interval estimation for use in routine MQA practice.

Level of service (LOS) has been widely used by MQA programs across the United States to characterize the condition of the highway facility. LOS provides a numeric score of overall facility condition or individual highway elements, such as roadside mowing and vegetation,

traffic signage, pavement markings, and drainage systems. Generally, a minimum LOS score of 80 is used to define an acceptable quality level.

Percent defective (PD) or percent within limits (PWL), which are simply different representations of the same measure, have a tremendous potential to assist MQA programs in evaluating the LOS of the overall highway facility and individual highway components. PD and PWL are currently widely used in the quality assurance field because they address both mean level and variability in a statistically efficient manner.

As presented in the original paper by Weed et al. (*2*), combining the LOS and PWL–PD measures offers highway agencies with a potentially more precise tool for developing an ordered list of highway segments in need of repair based on the current condition of the roadway. This is certainly useful information in its own right. In addition to this, if an effective way can be found to incorporate an economic (cost–benefit) analysis into this procedure, it has the potential to become not only an extremely effective prioritization tool for maintenance managers, it might also serve as a valuable research tool to study various maintenance strategies.

This paper illustrates the vital role that established statistical approaches, such as PWL and PD, can offer to MQA programs with emphasis on the LOS measure. First, current statistical practices in MQA are reported. Next, computational procedures for calculating the PWL using a personal computer or statistical software packages are presented. The percentage of LOS above a lower limit of 80 is calculated for the overall facility within a maintenance division, by highway functional class, by county, and by individual highway element. Confidence limits of the LOS are illustrated using a bar graph and ranked for future maintenance intervention. Finally, a cost-based approach for rehabilitating noncompliant segments is provided.

CURRENT PRACTICES IN MQA SAMPLING

Adams (*3*) reported on a survey of U.S. states and 10 Canadian provinces regarding MQA programs. Of the 39 responding agencies (36 states and three provinces), 83% indicated having some form of an MQA program used primarily for purposes such as condition assessment, maintenance work planning, maintenance policy analysis, and allocation of maintenance funds. MQA programs have been tailored for a wide range of features including culverts, guide rail, rest areas, traffic control devices, highways, bridges, and roadsides.

Ten lead states in MQA programs were further investigated to understand sampling and reporting statistics, with the goal of creating a statistics guide for MQA programs (*4*, *5*). Major maintenance categories for these programs were reported as pavement, unpaved shoulders, ditches and drainage, roadside features, traffic control devices, rest areas, and environmental concerns. Sampling plans and confidence intervals are summarized in Table 1.

Table 1 indicates that the majority of states conduct inspections over randomly selected sample units of length equal to 0.1-mi. North Carolina uses a 0.2-mi sample unit while New York and California use a 1-mi sample unit. For a given precision and confidence level, the necessary sample size should be a function of size of project or maintenance zone (i.e., population size), estimates of the population variance, desired precision rate, and desired confidence level (*6*–*9*).

TABLE 1 MQA Sampling Plans for Lead States

State (1)	Sampling Unit Length (2)	Confidence Level or Precision (3)	Computations (4)
California	1 mi	95% confidence level	LOS 2000 evaluation is based on visual inspection of randomly selected samples where approximately 10% of the inventory is surveyed.
Florida	0.1 mi	95% confidence level; 3% precision	Sampling is based on sample units within a maintenance section. A random number generator program is used to select the sample units on each facility type contained within a maintenance unit (*10*).
Indiana	0.1 mi	90% confidence level	Sample size for inspection of each of three functional classes (Interstates, U.S. highways, and state roads) per district is based on 90% confidence level (*11*).
New York	1 mi	N/A	600 random sections are selected from 10 participating regions for review every year by field personnel (*12*).
North Carolina	0.2 mi	90% to 95% confidence level; 6% precision	Sampling rate varies with resources; composite LOS computed using highway elements for pavement, unpaved shoulders and ditches, drainage, roadside, and traffic control devices (*13*).
Texas	0.1 mi	95% confidence level (varies)	Sample size is determined statistically as a function of tolerable error, confidence level, total number of sample units in the project, and an estimate of the population's standard deviation (*6*).
Utah	0.1 mi	N/A	Inspection is based on 25 randomly sampled units (*11*).
Virginia	0.1 mi	95% confidence level; 4% precision	Confidence level and precision level obtained from reports by de la Garza et al. (*8*); sample size determination based on work by Kardian and Woodward (*9*).
Washington	0.1 mi	95% confidence level	Statistical methods are used to identify approximately 2,200 randomly selected data survey sites around the state (*14*, *15*).
Wisconsin	0.1 mi	95% confidence level	Sample size of pavement condition is 100% sample of segments every other year. Sampling of other maintenance categories varies (*5*).

Many states use a composite equation to compute an overall LOS for a given highway segment. The calculation of LOS is typically based on observed characteristics relating to several primary elements associated with the highway facility, such as the pavement structure, drainage ditches, and traffic control systems. In North Carolina, for example, six primary elements are used, as shown in Table 2. Pavement or roadway condition is monitored with a separate *Pavement Condition Survey Manual* (*16*).

Smith et al. (*10*) reported two statistical quality measurement approaches used in LOS field inspections including method of attributes and method of variables. The method of attributes requires an observer to determine whether a certain standard has been achieved, and then recording the results in a yes–no or pass–fail fashion. It is therefore more qualitative than

quantitative but appears to be the popular method among highway maintenance agencies. The method of variables on the other hand, involves measuring and recording the numerical value according to a specified scale of measurement. It is more complicated than the attributes approach in that it requires both an approximately normal population and a greater number of calculations, but it is worth considering because it provides more precise estimates and narrower confidence intervals.

Summary statistics have also been applied in LOS ratings and analyses. To determine the LOS of a highway facility, each individual ratings for each sample unit is calculated and the statistical mean and variance are calculated for the overall LOS. According to Smith et al. (*10*) the mean and standard deviation for LOS can be calculated based on Equations 1 and 2, while the confidence interval is based on Equation 3.

$$\overline{\mathrm{LOS}_s} = \frac{\sum \mathrm{LOS}_{si}}{n} \tag{1}$$

$$s = \sqrt{\frac{\sum \left(\mathrm{LOS}_{si} - \overline{\mathrm{LOS}_s}\right)^2}{n-1}} \tag{2}$$

$$CI_{mean} = \overline{\mathrm{LOS}_s} \pm \left(Z * \frac{s}{\sqrt{n}} \right) \tag{3}$$

$$CI = \overline{\mathrm{LOS}_s} \pm \left(Z * s \right) \tag{4}$$

where

$\overline{\mathrm{LOS}_s}$ = mean segment LOS;
LOS_{si} = individual segment LOS values for n sample segments;
s = sample (estimated population) standard deviation of LOS rating;
n = number of sample units;
CI = confidence interval of LOS; and
Z = z-statistic for desired level of confidence (e.g., Z =1.96 for 95% confidence).

A weighting technique is typically used to obtain an overall segment LOS from individual elements (e.g., traffic signage, vegetation). The overall LOS for a sample unit or segment is calculated as shown by Equation 5.

$$\mathrm{LOS}_s = \frac{\sum_{j=1}^{N} \mathrm{LOS}_j W_j}{\sum_{j=1}^{N} W_j} \tag{5}$$

TABLE 2 Elements and Characteristics Monitored for LOS (*13*, *16*)

Element (1)	Monitored Characteristics (2)
Pavement	Flexible pavement: alligator cracking, block cracking, reflective cracking, rutting, raveling, bleeding, ride quality, and patching. Rigid shoulder features: shoulder lane joint, shoulder drop-off, and shoulder condition. Rigid pavement features: patching, surface wear, pumping, ride, longitudinal cracking, transverse cracking, corner break, spalling, joint seal, and faulting.
Unpaved shoulders and ditches	Shoulders, lateral ditches, and lateral ditch erosion.
Roadside	Brush and tree control, turf condition, litter and debris (1998).
Drainage	Crossline pipes blocked, crossline pipes damaged, gutters blocked, inlets (blocked or damaged).
Traffic control devices	Pavement striping, words and symbols, pavement markers.
Environmental	Turf condition (1998), miscellaneous vegetation management (1998).

where

LOS_S = overall LOS for sample unit or segment;
LOS_j = LOS for element j with some observed characteristics;
W_j = assigned weight for element j with observed characteristics for a particular highway functional classification (e.g., 30% pavement, 14% drainage); and
N = total number of elements with observed characteristics.

PWL TO SUPPLEMENT CURRENT PRACTICE

Sample Size and Confidence Interval

As reported from the 10 lead states, sample size and the confidence of population estimates are a fundamental component of the MQA program. Equations 1, 2, and 3 are appropriate to determine the number of sample segments for the estimated LOS at the statewide, district, or county level provided that there is a reasonable population estimate for variability. There are four interrelated components to these equations that can be evaluated, including: (*1*) confidence limits of the sample, (*2*) *Z*-statistic for the desired probability level, (*3*) estimated standard deviation, and (*4*) number of samples. As Equation 3 implies, there is a lesser number of samples required when the confidence limits are broadened, when the confidence probability level is reduced or when the standard deviation is relatively small. Reasonable estimates for the standard deviation can be found from collected data within each MQA program.

Opportunity to Use the PWL Approach

There is an opportunity to characterize and measure the quality of maintenance using an alternative approach, while building upon the successes and previous practices of confidence interval estimation. The approach is adopted from current practices of most state highway

agencies that accept pavement material from a contractor and pay that contractor through a system of incentives and disincentives. The FHWA has recommended the use of PWL as the quality measure (*17*). A recent NCHRP Synthesis found that almost two-thirds (29 of 45) of the states use PWL (or its complement, PD) as the quality acceptance measure (*18*). The FAA solely uses PWL for acceptance of airfield pavement construction work with the P-401 specification for asphalt pavement and P-501 specification for concrete pavement (*19*, *20*).

PWL, also called percent conforming, is the percentage of the lot falling above the lower specification limit (LSL), beneath the upper specification limit (USL), or between the USL and LSL (*17*, *21*). PD is similar to the PWL, however, the percentage of lot falling outside the specification limits is reported. PWL and PD both use the sample mean and the sample standard deviation to compute a quality (Q) statistic which is then entered into published tables or special computer software to estimate the percentage of the population (lot) that is within (or outside of) the specification limits. It is similar in concept to determining the area under the normal curve. In theory, the use of the PWL method assumes that the population being sampled is normally distributed. In practice, it has been found that statistical estimates of quality are reasonably accurate provided the sampled population is at least approximately normal (i.e., reasonably bell shaped and not bimodal or highly skewed). A recently published guide for using statistics in MQA programs found that many sampled highway features are approximately normal (*4*, *5*). If desired, standard normality tests can verify whether the normality assumption is sufficiently well met.

PWL History and Requirements

This methodology is generally referred to as "variables acceptance sampling" and one of the earliest documents was published by the U.S. Department of Defense as Military Standard 414 (*22*) in which, and in separate publications, the basic theory and assumptions are explained. The American Society of Quality (ASQ) in conjunction with the American National Standards Institute (ANSI) further improved the initial work in MIL-STD-414 to create PWL tables for a given lot size and AQL. These standards and tables have been published ANSI–ASQ Z1.9, BS6002, and ISO 3951 (*23*). This area was advanced further with a computer program developed by Weed (*24*) for the FHWA to assist agencies in assessing the risks associated with the acceptance procedure using PWL or PD.

Random sampling, similar to the current approach of lead states in MQA, is a primary requirement of PWL. Each pavement segment must be given an equal chance of being selected. If there is 100% sampling, the random sampling requirement is superceded by having all possible samples included in the population data set.

Calculating PWL Using the Beta Distribution

The beta distribution is the underlying mathematical distribution from which PWL estimates can be obtained, and the necessary computations can be performed using spreadsheets (ASQ, Microsoft Excel) or statistical software packages such as Statgraphics, Statistical Analysis Software, or Minitab. A series of steps and equations reported by Freeman and Grogan (*25*) were followed in performing PWL computations. Once the sample size has been determined and the mean and standard deviation have been calculated, the first step is to calculate the α and β shape factors. The equation for α and β are

$$\alpha = \beta = \frac{n}{2} - 1 \text{ for } n \geq 3 \tag{6}$$

$$\alpha = \beta = \frac{1}{4} \text{ for } n = 2 \tag{7}$$

where

α and β = shape factors and
n = size of sample.

Once α and β have been determined, a Q value is determined through the following equation, where the lower limit for LOS is traditionally set at 80.

$$Q(\text{lower}) = \frac{\text{Lower Limit} - \text{Mean}}{\text{Standard Deviation}} \tag{8}$$

An x value is then calculated in order to use the beta distribution. It is found using previously defined Q and n values, and the following equation:

$$x = \frac{1}{2}\left(1 - \frac{Q\sqrt{n}}{n-1}\right) \tag{9}$$

Once these values have been determined, the PWL is calculated. The PWL value represents the percentage of values in the sampled population that are above a single lower limit, below a single upper limit, or between a pair of lower and upper limits. One method of computing PWL is Microsoft Excel spreadsheet software, as reported in previous work by Gharaibeh et al. (*6*), in the following:

$$\text{PWL} = \text{BETADIST}(x, \alpha, \beta, A, B) \tag{10}$$

where

x = shape function (previously defined);
α and β = shape factors (previously defined);
A = lower limit of distribution, if nothing entered, assumed to be 0; and
B = upper limit of distribution, if nothing entered, assumed to be 1;

This function yields values which conform to the tables usually used to determine beta distribution probability functions.

EXAMPLE CALCULATIONS FOR PWL

To illustrate use of this procedure, actual maintenance data describing the condition of various highway components were accessed from North Carolina Department of Transportation. Data were readily available from development of a statistics guide for MQA programs. A feature of

North Carolina MQA data was that random 0.2-mi segments are sampled within each mile of roadway for the features shown in Table 2. LOS for individual features, and overall LOS for the segment, is computed.

An initial step is to define exactly what is or is not acceptable in terms of the statistical measure. In highway MQA applications, a mean LOS ≥ 80 is often chosen as the acceptable quality level (AQL), defining that the sample (or population) mean lies at or above 80. However, the potential weakness of this method is the fact that it ignores the effect of variability. Depending on the dispersion of the population, typically measured by the standard deviation, the mean LOS could be greater than 80 (and thus be judged acceptable) while nearly half of the population might actually be lower than 80 (which some maintenance engineers might judge to be unacceptable). The PWL method offers a way out of this dilemma by making it possible to estimate what percentage of the population actually falls below the lower limit of 80.

An example of PWL calculations for overall LOS values in County 1 are presented in Table 3. All segments in the county were sampled, thus the standard deviation was calculated based upon a population estimate.

The calculations in Table 3 provide an important indication of highway maintenance performance in County 1. First, the mean LOS = 85.1 indicates that an AQL is being achieved since the mean LOS is operating above the lower threshold of 80. Computation of the PWL identifies that, coupling the mean with variability, County 1 has 79.7% of highway segments within an acceptable LOS condition. The PD of highway segments in County 1 is 20.3% (100% – 79.7%). An LOS=80 would expect to yield a PWL=50%.

This approach provides a new perspective since both mean level and variability are similarly important in evaluating highway components based on LOS. It can provide emphasis in maintenance management that focuses on identifying unsatisfactorily performing areas or sections, as well as a proactive approach to anticipate poorly performing areas.

TABLE 3 PWL Computations for County 1 Maintenance Condition

Step (1)	Variable and Equation (2)	Numerical Calculation (3)
1	Basic summary statistics	Sample size = 142; average LOS = 85.1; standard deviation LOS = 6.2
2	α and β using Equation 6	$\alpha = \beta = \frac{N}{2} - 1 = \frac{142}{2} - 1 = \mathbf{70}$
3	Q using Equation 8	$Q(\text{lower}) = \frac{\text{Lower Limit} - \text{Mean}}{\text{Standard Deviation}} = \frac{80 - 85.1}{6.2} = \mathbf{-0.82}$
4	x using Equation 9	$x = \frac{1}{2}\left(1 - \frac{Q\sqrt{n}}{n-1}\right) = \frac{1}{2}\left(1 - \frac{-0.82\sqrt{142}}{142-1}\right) = \mathbf{0.535}$
5	PWL using Equation 10	$\text{PWL} = \text{BETADIST}(x, \alpha, \beta, A, B) = \text{BETADIST}(.535, 70, 70, 0,1) = \mathbf{79.7}\%$

GRAPHICAL DISPLAY OF LOS CONFIDENCE INTERVAL WITH PWL VALUE

The previous example illustrated how the MQA program can estimate the percentage of segments above a prescribed threshold limit. Next, the agency can be afforded an overall picture of maintenance condition throughout the state, district, or county by computing and graphically illustrating the confidence interval of the LOS with respect to the acceptable threshold (LOS ≥ 80). The entire state MQA data set was stratified by (*a*) 14 transportation districts, (*b*) four functional classifications of Interstate, primary, secondary, and urban highways with each district, and (*c*) counties within each district (ranging from five to eight). This stratification approach assists a transportation district in managing a variety of functional class roadway segments and locations (counties) of those segments.

The process began by arbitrarily selecting District 9 having five counties, with each county containing the four functional class highways, except County 85 not having Interstate highways. First, for each functional class within each county, the PWL was computed using the mean, standard deviation, and sample size with the beta distribution. Table 4 illustrates the PWL calculations for the five counties in District 9.

TABLE 4 District 9 PWL Computations for Maintenance Condition

County (1)	Functional Class (2)	*N* (3)	Mean, LOS (4)	Std. Dev., LOS (5)	α, β (6)	Q (upper) (7)	*x* (8)	PWL (%) (9)
85	Interstate	0	N/A	N/A	N/A	N/A	N/A	N/A
	Primary	5	79.0	7.7	1.5	0.130	0.464	45
	Secondary	71	73.0	5.7	34.5	1.230	0.426	11
	Urban	72	80.2	7.5	35.0	–0.031	0.502	51
80	Interstate	3	80.3	2.5	0.5	–0.134	0.558	54
	Primary	28	84.3	6.3	13.0	–0.676	0.566	75
	Secondary	33	79.5	6.7	15.5	0.073	0.493	47
	Urban	94	84.8	7.3	46.0	–0.655	0.534	74
34	Interstate	5	77.8	3.8	1.5	0.585	0.337	30
	Primary	36	80.9	6.8	17.0	–0.135	0.512	55
	Secondary	23	78.0	7.7	10.5	0.266	0.471	40
	Urban	129	78.9	6.9	63.5	0.167	0.493	43
30	Interstate	5	83.4	2.7	1.5	–1.247	0.848	90
	Primary	27	82.7	8.0	12.5	–0.338	0.534	63
	Secondary	13	80.1	5.4	5.5	–0.014	0.502	51
	Urban	27	86.8	7.0	12.5	–0.964	0.596	83
29	Interstate	12	79.3	4.9	5.0	0.137	0.478	45
	Primary	17	81.2	7.4	7.5	–0.160	0.521	56
	Secondary	57	78.6	7.5	27.5	0.193	0.487	42
	Urban	128	84.4	6.9	63.0	–0.637	0.528	74

The 95% CI for the LOS of each functional class by county were computed using Equation 4, then graphically prepared using horizontal bars and ranked according to functional class, as illustrated in Figure 1. It was assumed that the data were normally distributed when creating the confidence bands. The following is a sample confidence interval calculation for Interstate highway segments in County 29:

$$\text{Upper Confidence Limit}_{\text{Interstate, County 29}} = 79.3 + (1.96)(4.9) = 88.9$$

$$\text{Lower Confidence Limit}_{\text{Interstate, County 29}} = 79.3 - (1.96)(4.9) = 69.7$$

Figure 1 offers important insight as to county performance and functional class performance. In general, Counties 34 and 85 had mean LOS for three functional classes at or below the required threshold of 80. Interstate highways had the smallest CI (lowest variability). Secondary highways generally had a lower mean level and PWL of the functional classes, with County 85 having only PWL = 11% for secondary highway segments at or above LOS = 80.

These initial CIs provide an important visual summary of maintenance performance. Elongated bars, whether the mean is above or below LOS = 80, indicate there is service variability among highway segments within the particular functional classes. Maintenance engineers can further investigate substantially wider intervals or those where the mean level is much lower than comparable functional classes.

The maintenance performance of Interstate highways in County 29 were investigated to understand why only 45% of segments were LOS ≥ 80. The LOS interval by highway element was graphed to identify target areas where performance could be improved. Figure 2 illustrates the confidence intervals, denotes the mean LOS, and estimates percentage of segments (PWL) having LOS ≥ 80.

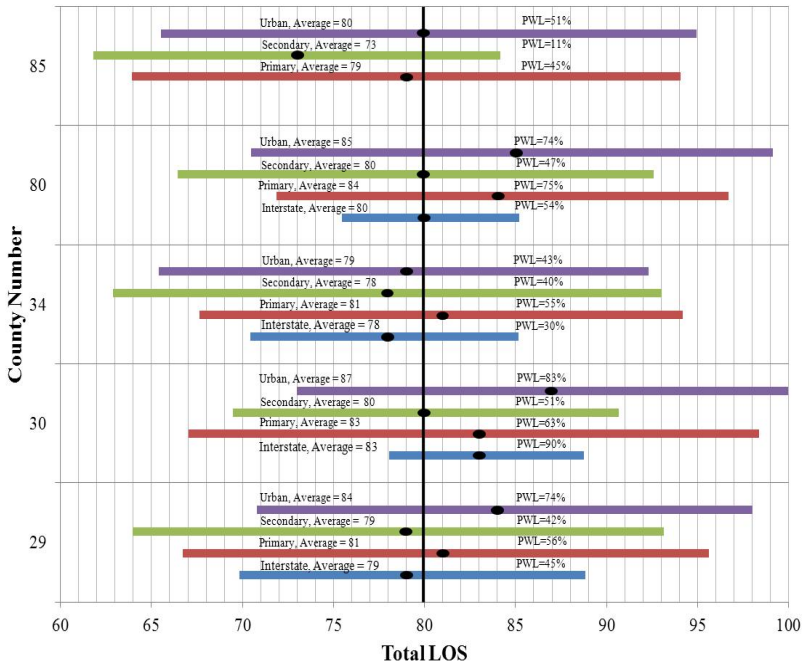

FIGURE 1 Ranking of District 9 PWL by functional class and county.

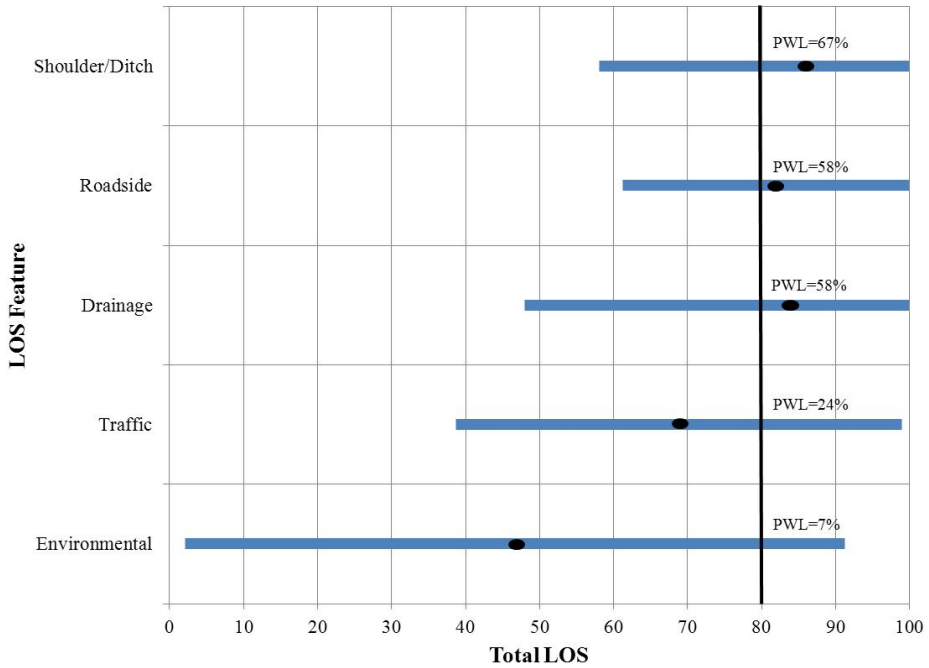

FIGURE 2 Ranking of LOS elements for Interstate segments in County 29.

Figure 2 indicates that mean LOS for traffic and environmental elements are lower than the other elements, and that environmental has a greater amount of variability as denoted by the widest confidence band. LOS bands above 100 were truncated for illustrative purposes. In addition, the PWL measures for traffic and environmental are 24% and 7%, respectively. If there were higher mean levels and less variability for these elements, the weighted mean LOS for Interstate highways in County 29 would have been greater.

COST OF IMPROVING DEFICIENT SEGMENTS

Maintenance activities to bring highway segments into compliance obviously have a cost. Accessing historical cost data and identifying the number of non-compliant segments provides an estimate of expenditures necessary to bring the segments back into compliance. Clearly, a higher PWL will require more resources; thus, the agency may want to consider the cost-benefits of routine or added maintenance to achieve substantially higher PWL scores.

An example of the trade-off between maintenance activities (cost) and performance quality (benefit) was prepared using maintenance cost data reported by Adams (*26*). Table 5 reports the average cost per lane mile to maintain higher-end highways for several maintenance categories in three Midwestern states. There is a wide disparity among these unit prices, so an overall average was computed for example purposes. It must be noted that there must be careful scrutiny of using any unit prices in the cost–benefit analysis since they must take into account the quantity of work (lower quantities having higher unit prices), traffic levels, crew productivity, location, scope of maintenance activity, and other factors.

The previous section presented lower LOS scores for traffic and environmental elements of Interstate highway in County 29. Next, a goal is established for achieving a mean LOS ≥ 80

for each element of the Interstate highway segments. A review of the 12 Interstate segments found that additional environmental maintenance to 11 of 12 lower-performing segments, and additional traffic maintenance to five of 12 segments, would achieve an LOS = 80 for each element. Table 6 summarizes the key statistics for the original service level and post-improvement service level, as well as cost of added improvements. Figure 3 illustrates the increase in mean LOS and reduction in variability with these maintenance activities. Assuming a four-lane Interstate highway and 1-mi segments, the maintenance cost to improve the LOS = 80 for environmental and traffic is estimated at $19,452 and $4,095 among a 12-mi segment of Interstate, respectively.

TABLE 5 Average Cost per Lane-Mile for Common Maintenance Functions for High-End Highways (*26*)

Element (1)	Michigan Average (2006), $/lane mile (2)	Ohio Average (2006), $/lane mile (3)	Wisconsin Average (2006), $/lane mile (4)	State Average (2006), $/lane mile (5)
Roadway	682.75	988.52	345.39	672.22
Shoulders and ditches	163.31	227.42	156.72	182.48
Drainage	241.70	936.28	113.04	430.34
Roadside–environmental	466.11	611.70	248.42	442.08
Traffic control	109.70	363.34	141.16	204.73

TABLE 6 Cost to Improve Deficient Segments for Environmental and Traffic

	Environmental		Traffic	
	Original	After Improvement	Original	After Improvement
N	12	12	12	12
Sections improved	—	11	—	5
LOS average	47	81	69	80
LOS, std. deviation	22.8	3.0	15.4	6.8
α, β	5.0	5.0	5.0	5.0
Q (upper)	1.465	–0.302	0.725	–0.012
x	0.269	0.547	0.386	0.502
PWL	7%	62%	24%	50%
No. of lanes	4	4	4	4
Cost per lane mile	—	$442	—	$205
Total Cost	—	$19,452	—	$4,095

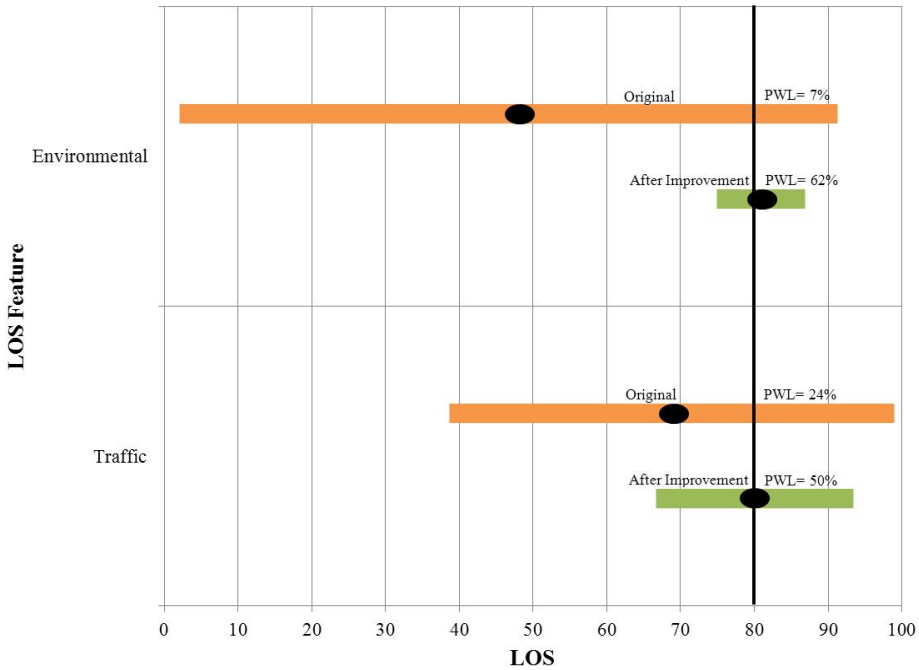

FIGURE 3 Comparison of LOS elements: original and postimprovement for County 29.

The agency must weigh this cost against achieving the benefit of achieving an LOS ≥ 80 if that is the goal of the program. A goal of compliant segments to achieve a minimum LOS of 80 must be factored in the agencies budgeting and timing of maintenance intervention. This example incorporated unit prices that may not be applicable to the given segments; however, it does provide an approach for the agency to consider when ranking and determining maintenance treatments and schedules.

SUMMARY AND CONCLUSIONS

This paper presented a statistically-based ranking procedure using the LOS and PWL measures to assist in highway maintenance management decisions. LOS and PWL are two of the most widely used measures in their respective fields of maintenance management and highway quality assurance. This approach incorporated both the mean level and variability of highway segments and components based on LOS.

Current statistical practices in MQA were reported. Computational procedures for calculating the PWL using a personal computer or statistical software packages were presented. PWL computations originate from the beta distribution and Military Standard 414. Actual LOS data from a state were sampled and analyzed to determine those segments in greatest need of maintenance or rehabilitation, based upon a minimum acceptable LOS = 80 and PWL ranking from highest to lowest. The entire state MQA data set was stratified by transportation districts, four functional classifications (Interstate, primary, secondary, and urban highways), and counties within each district. A 95% CI of the LOS values were constructed using the mean and standard deviation, with the assumption that the data were normally distributed.

Data from one transportation district found two of five counties had mean LOS for three functional classes at or below the required threshold of LOS = 80. Interstate highways had the smallest CI (i.e., lowest variability). Secondary highways generally had a lower mean level and PWL of the functional classes, with one county having only PWL = 11% of secondary segments at or above LOS = 80. This stratification approach provided a statistically based illustration of transportation district performance to manage a variety of functional class roadway segments and locations (counties) within the management district.

A cost-based approach for the agency to consider when ranking and determining maintenance treatments and schedules was provided. An analysis of 12 Interstate segments in one county found that additional environmental maintenance to 11 of 12 lower-performing segments, and additional traffic maintenance to five of 12 segments, would achieve an LOS = 80 for each element. The maintenance cost to achieve an LOS = 80 for environmental and traffic was estimated at $19,452 and $4,095 among a 12-mi segment of Interstate, respectively.

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MAINTENANCE OF ROADWAYS AND ROADSIDES

Wet-Night Visibility of Pavement Markings
Research and Test Methods

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Research has shown that pavement marking visibility is most difficult to achieve during nighttime rainy conditions. While wet markings have shorter visibility distances than dry markings, wet markings combined with rainy conditions lead to the shortest visibility distances. The pavement marking industry is producing more and more innovations to level the playing field and provide adequate wet-night visibility of pavement markings. As more innovative solutions are being developed, ASTM is developing and making available standardized test methods so that measurements can be made in a standardized way. The research and test methods facilitate opportunities to develop pavement marking performance specifications that can include dry, wet recovery, and continuous wet pavement marking retroreflectivity levels.

Longitudinal pavement markings are one of the most important means of communicating the separation of lanes of travel and the roadway alignment. Therefore it is important to design and use pavement markings that are both durable and cost-effective while also being able to provide effective lane guidance under normal and poor visibility conditions. In particular, nighttime rainy conditions tend to be the most difficult condition for pavement markings to achieve adequate performance. New pavement marking systems are constantly being deployed in an effort to provide adequate performance during these tough conditions. Because of the increased emphasis on provide wet nighttime pavement marking performance, more attention has also been allocated toward the research and test methods available to measure pavement markings under wet conditions.

The performance of pavement markings is reduced under wet-night conditions because of several reasons. When it is raining, the headlamp illumination scatters through the rain and less light reaches the pavement marking. Another factor is the water on the surface of pavement markings. The accumulated water scatters the incoming light through specular reflection and refraction, which reduces the amount of light retroreflected. Subsequently, the reduction in retroreflected light directly relates to a reduction in detection distance. The resulting shorter detection distance creates a more demanding driving situation for the driver and a potentially less safe driving environment. Figure 1 shows a glass bead embedded in a pavement marking binder and retroreflecting light.

There are a number of available technologies that may be used to improve the wet-night visibility of pavement markings. Some of these technologies are

- Larger glass beads,
- High refractive index glass beads,
- Composite optics (small optics fixed to the surface of a larger core),
- Structured tapes,

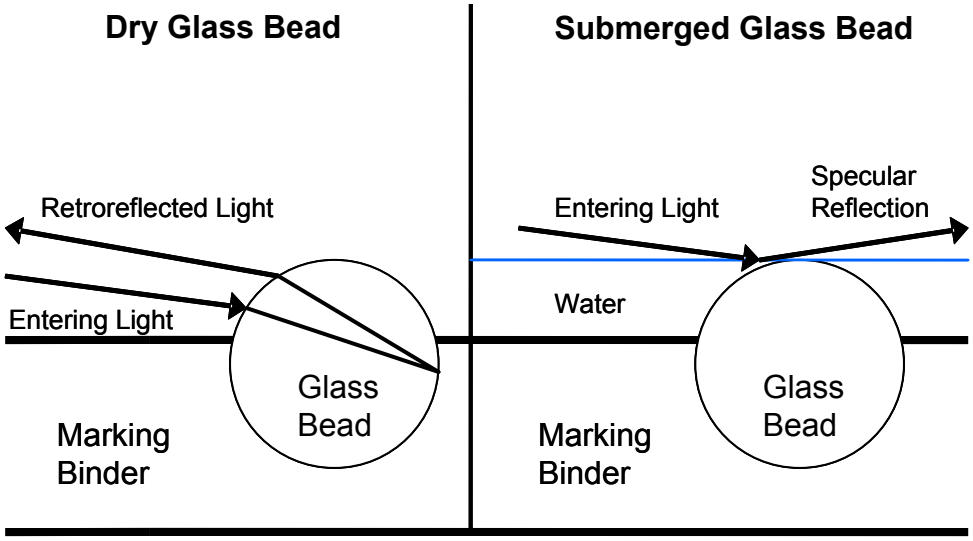

FIGURE 1 Glass bead retroreflection (*1*).

- Profiled markings, and
- Rumble stripes.

BACKGROUND

Research has shown that pavement markings exhibit a positive correlation between detection distance and level of retroreflectance. Early studies conducted by Schnell et al. (*2–4*) show this positive correlation. Figure 2 shows some results of the studies conducted by Schnell et al.

Schnell et al. also conducted some of the first work to quantify the performance of different types of pavement markings under dry, wet, and simulated rain conditions (*5*). An example of the detection distance results for three marking types can be seen in Figure 3. Due to the short detection distances, drivers most likely overdrive their headlamps under rainy conditions. It should be noted that the rainfall rate used for this experiment was 1 in./h.

The Virginia Tech Transportation Institute (VTTI) has conducted several tests associated with the wet-night visibility of pavement markings. Their first test was a static evaluation of six pavement marking types (*6*). The markings were viewed by subjects over 60 years of age, under a simulated rainfall of 0.8 in./h of rainfall at night. Both a sedan and a truck tractor were used as the viewing vehicle in which the subjects sat while viewing the markings.

The results of the visibility study for the sedan under the continuous rain and dry conditions can be seen in Figure 4. From the figure a large decrease in visibility distance can be seen during the rainy condition versus the dry condition.

In a follow-up study, VTTI evaluated the performance of four pavement markings under wet-night conditions using a dynamic testing protocol (*7*). Participants were asked to detect the end points of the markings in rainy and clear conditions. Figure 5 shows that there results were similar to previous findings in that pavement marking detection distances tend to decrease from conditions starting at dry, then recovery, and then raining.

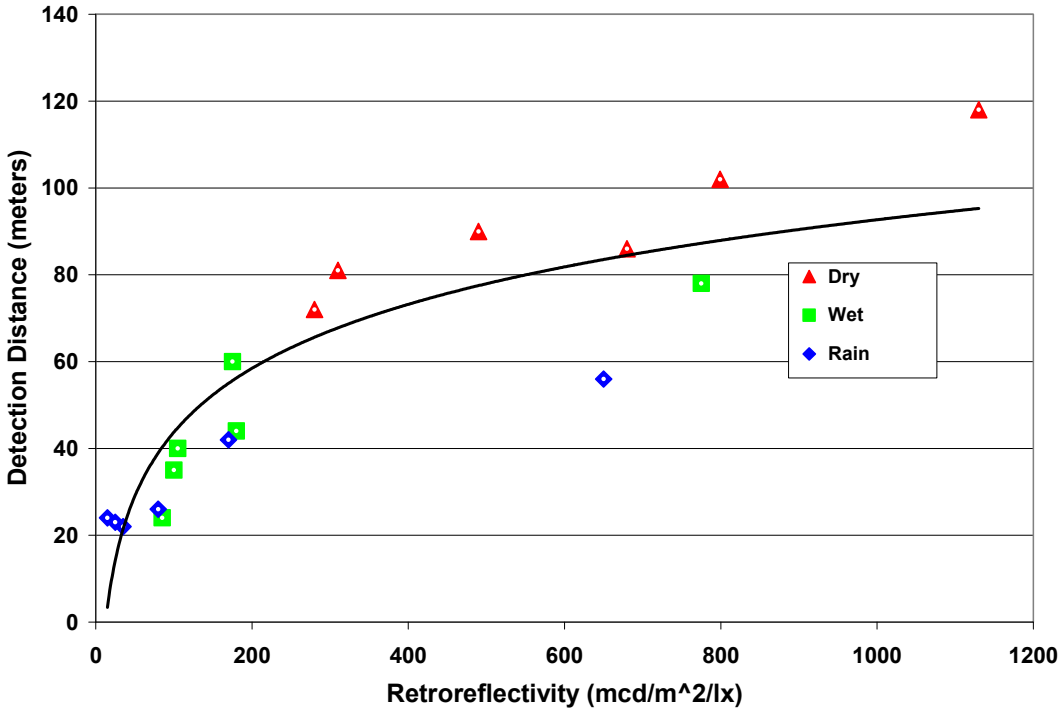

FIGURE 2 Relationship between retroreflectivity and detection distance.

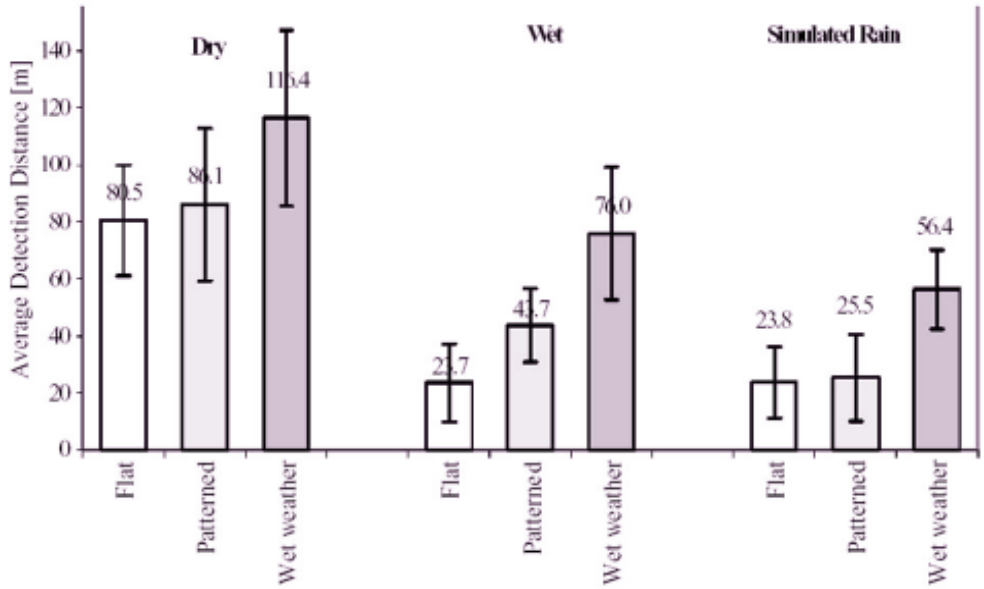

FIGURE 3 Example of marking detection distances (5).

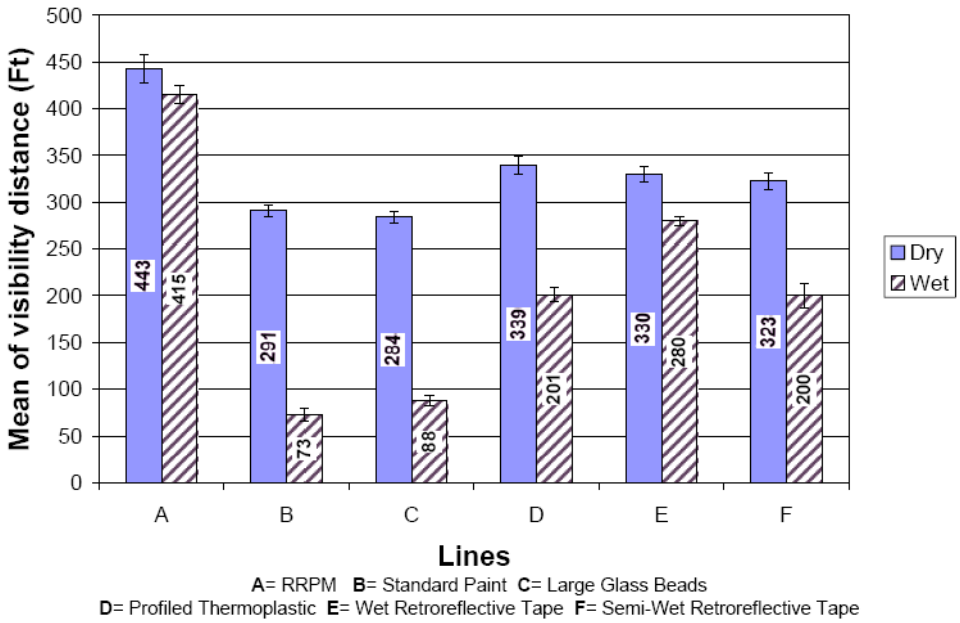

FIGURE 4 Sedan: saturated evaluation. Results of the visibility distance for the condition *x* line interaction (*6*).

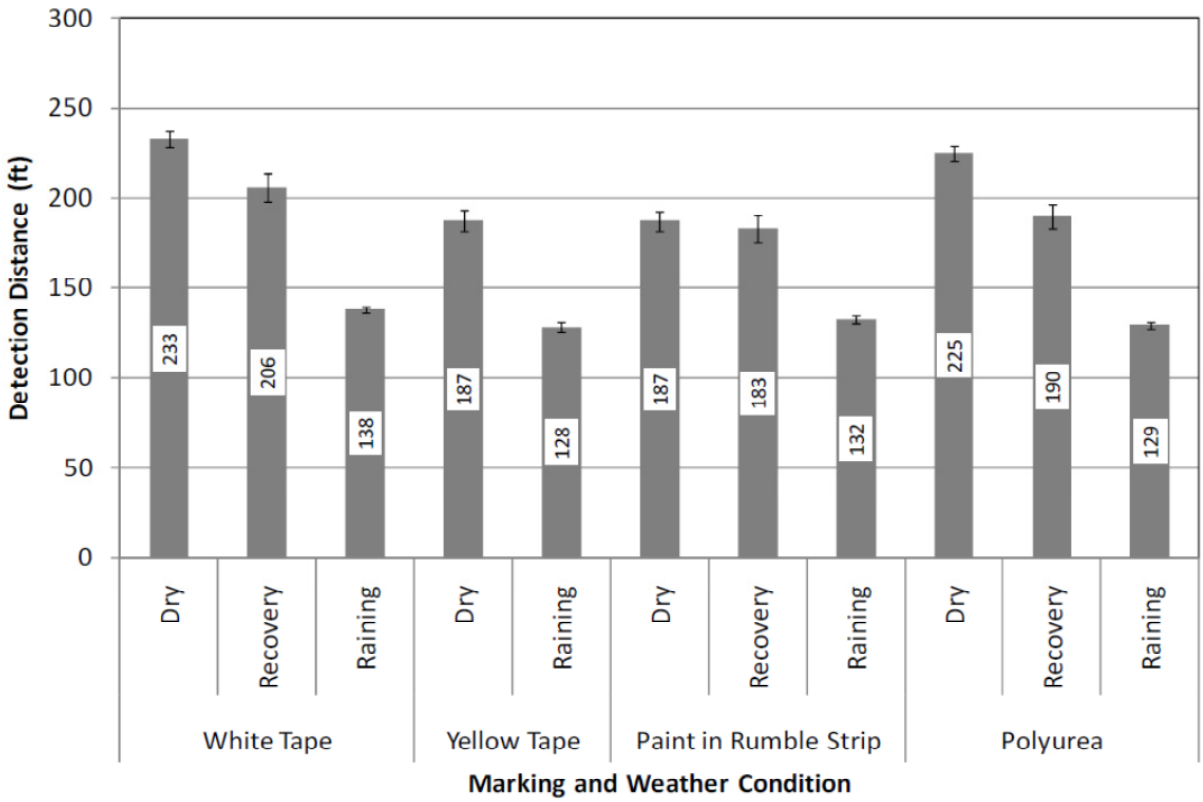

FIGURE 5 Mean detection distances from VTTI (*7*).

The Texas Transportation Institute (TTI) conducted perhaps the most comprehensive evaluation of pavement markings under wet conditions. Two research reports were developed. The first report contains the literature review on wet-night markings and reports the Phase I effort on performance of wet-night pavement markings (*1*). The second report contains the Phase II effort on performance of wet-night pavement markings and includes a benefit–cost analysis (*8*). An example of the findings by rainfall rate is shown in Figure 6.

A common finding of these studies is that during nighttime conditions pavement markings are most visible under dry conditions and their visibility is severely limited when they are wet. However, the conditions of being wet are important. When pavement markings are only wet but no rain is falling (i.e., after a rain event), their performance is better than during rain events. Furthermore, the intensity of the rain impacts their visibility as well. The more intense the rain is, the less visible the pavement markings are.

TEST METHODS FOR PAVEMENT MARKING RETROREFLECTIVITY

ASTM E1710 describes the standard test method for measuring pavement marking retroreflectivity in dry conditions (*9*). This is currently the most commonly referenced test method for measuring pavement marking retroreflectivity. ASTM D7585 describes a standardized sampling protocol that can be used to assess to performance of pavement markings in a statistically robust manner (*10*).

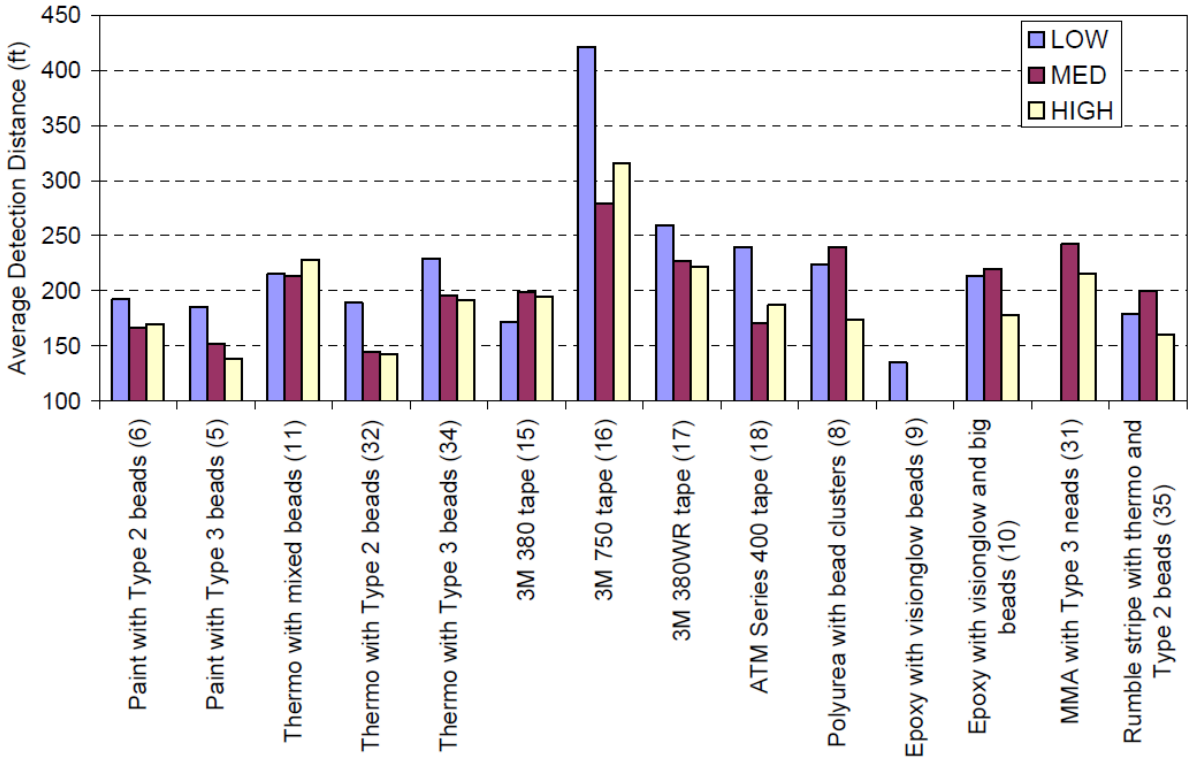

FIGURE 6 Mean detection distance from TTI, where low = 0.28 in./h, medium = 0.52 in./h, and high = 0.87 in./h (*1*).

ASTM E2177, Standard Test Method for Measuring the Coefficient of Retroreflected Luminance (R_L) of Pavement Markings in a Standard Condition of Wetness, is a procedure that measures marking retroreflectivity after water has been poured on the marking and allowed time to drain off the marking (*11*). It is also referred to as the "recovery" or "bucket" method. It is intended to represent the retroreflectivity of a marking material after rain has stopped and the marking is still wet. It can also represent marking retroreflectivity in conditions of dew or high humidity. The procedure states that the wetness state can be created with a hand sprayer or a bucket of water. If a sprayer is used, the marking should be sprayed for 30 s. If a bucket is used, 2 to 5 L of water should be slowly poured over the marking. With either wetting procedure, the marking's retroreflectivity is measured 45 ± 5 s after the spraying or pouring is completed.

ASTM E2176, Standard Test Method for Measuring the Coefficient of Retroreflected Luminance (R_L) of Pavement Markings in a Standard Condition of Continuous Wetting, is a procedure where water is continuously sprayed on the marking while measuring retroreflectivity (*12*). It is intended to represent the retroreflectivity of a marking material during a rain condition and is also referred to as the "spray" method. The procedure specifies that the spray area should be a 20 ± 2 in. diameter circle, that the spray head height should be 18 ± 6 in., and that the spray rate should be 0.8 ± 0.2 L/min. This spray rate equates to a rainfall rate of about 9.32 in./h. However, the tolerances associated with various aspects of this standard procedure can result in a rainfall rate anywhere in the range of 5.78 to 14.39 in./h. E2176 indicates that the rate of spray may influence the results of the measurements, but a note in the procedure states that the effects of changes in spray rate, height, and area are minimal. These statements conflict with each other and the procedure provides no support for the accuracy of either statement. After initiating the spray condition, the user should wait 10 to 15 s before making measurements. Readings should be taken about every 10 s until a steady state is achieved, which usually takes about 30 s.

Because of a general lack of repeatability and user confidence, efforts have been underway within ASTM to replace ASTM E2176 with new test method for testing pavement markings under raining conditions. Through a series of research projects and industry testing, ASTM Work Item 19806 (WK19806) was developed and evaluated. Formal testing was completed in Florida in early 2011. As of December 2011, ASTM WK19806 has been approved by the ASTM subcommittee E12.10 and now awaits formal adoption by the ASTM main committee of E12 in February 2012. Once a new test method is officially adopted (expected in the spring of 2012), ASTM will begin the process of rescinding ASTM 2176.

The repeatability of ASTM WK19806 was evaluated in Florida in 2011. Measurements of pavement markings approximately one year old were taken along the edge line of a rural state highway. Results of the testing are shown Table 1. Note that the first type of pavement marking is generally considered to have no wet-night performance and the results of the testing were as expected. The other products tested were specifically designed to have good wet-night performance.

An overall comparison of the three ASTM test methods using measurements taken from a pavement marking test deck on an Interstate highway is shown in Figure 7. These measurements include both the edge line and lane line. They demonstrate a point made in several of the research studies summarized above—dry retroreflectivity levels are not indicative of wet retroreflectivity levels.

TABLE 1 Testing of ASTM WK19806

Pavement Marking Description	Average	Repeatability	Repeatability/Average (%)
Thermoplastics with a single drop of AASHTO M247 Type 1 beads.	9	8	84
Thermoplastics with a double drop of AASHTO M247 Type 3 beads and composite optics, which are independently retroreflective optics.	118	72	63
Inverted rib thermoplastics with a double drop of AASHTO M247 Type 1 and glass beads with an index of refraction of 1.9.	476	115	24
Thermoplastics with a double drop of AASHTO M247 Type 1 and AASHTO M247 Type 4 beads.	162	40	25
Thermoplastics with a double drop of AASHTO M247 Type 3 and composite optics, which are independently retroreflective optics.	143	52	36

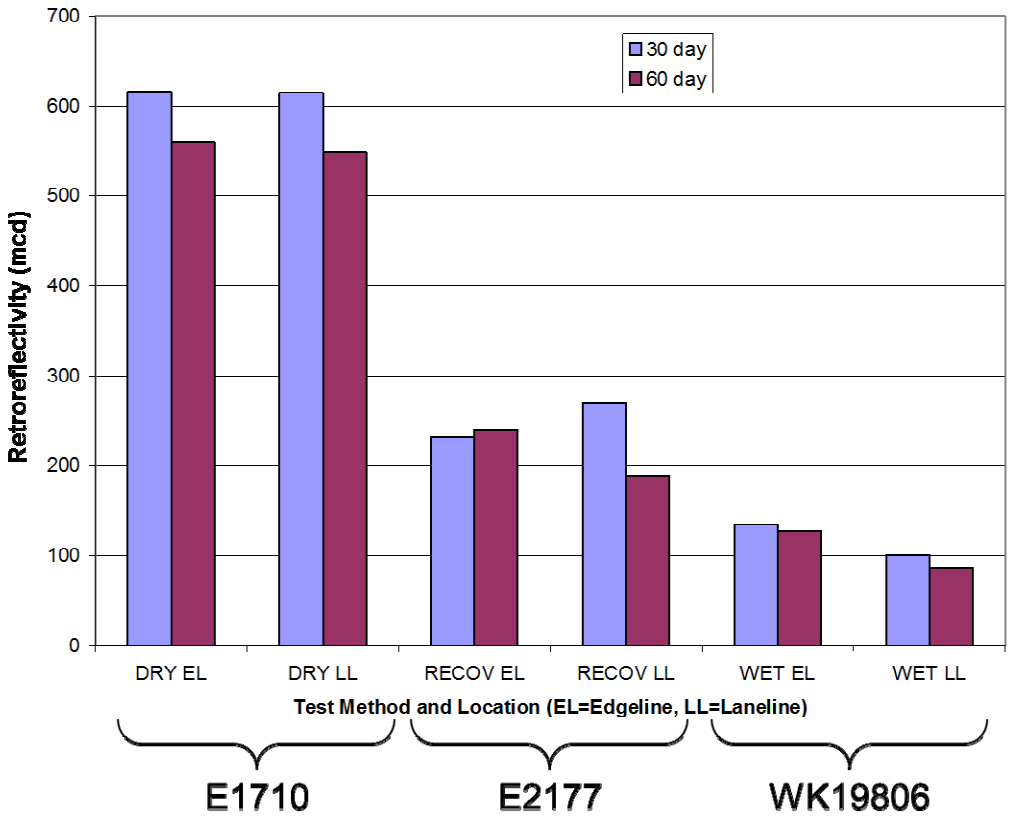

FIGURE 7 Comparison of ASTM test methods for measuring pavement marking retroreflectivity.

SUMMARY

Research has shown that pavement marking visibility is most difficult to achieve during nighttime rainy conditions. While wet markings have shorter visibility distances than dry markings, wet markings combined with rainy conditions lead to the shortest visibility distances. The pavement marking industry is producing more and more innovation to level the playing field and provide adequate wet-night visibility of pavement markings. As more innovative solutions are being developed, ASTM is developing and making available standardized test methods so that measurements can be made in a standardized way. The research and test methods facilitate opportunities to develop pavement marking performance specifications that can include dry, wet recovery, and continuous wet pavement marking retroreflectivity levels.

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MAINTENANCE OF ROADWAYS AND ROADSIDES

Developing Effective Traffic Control Devices and Roadway Lighting Maintenance Management Programs

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Traffic control devices (TCDs) (signals, beacons, signs, and markings) and roadway lighting systems need proper preventive maintenance. This includes systematic inspection, cleaning, adjusting, repair, and replacement. Inadequate maintenance of traffic signals causes more malfunctions resulting in accidents and delays. Poor upkeep of signs (regulatory, warning, and advisory) and pavement markings also increases the risk of accidents. Inoperable street lights severely reduce safety and security. Public entities have been found liable for failure to sufficiently maintain these systems. Too often state and local transportation–public works agencies defer regularly scheduled maintenance because of other demands on time and money. More emphasis is placed on reactive maintenance: replacing a missing stop sign, fixing a faulty signal, or reinstalling a damaged street light for instance. Other non-emergency work such as installing, removing, or changing signs due to engineering work orders or adding intelligent transportation system components to signals, for example, usually get higher priority. Likewise, compliance with unfunded federal mandate deadlines, such as for school zone and street name sign upgrades, typically use funds that are needed for routine maintenance. The problem is becoming more acute as traffic maintenance work-staffs are permanently reduced due to chronic budget shortfalls. Illegible, missing and obsolete signs, signals that frequently malfunction, and multiple inoperable street lights are indicators of lack of proper maintenance. This leads to a negative perception by the public as TCDs affect nearly everyone, every day. Developing, implementing, and sustaining an effective preventive maintenance program should be the primary responsibility of a traffic operations manager. There are a number of reference sources such as manuals and handbooks that are available. But, aside from the technical aspects, it is very important that traffic operations managers have a good grasp of administrative functions such as budget forecasting, purchasing and inventory control, and project scheduling. Work force development, particularly training, guidance, and motivation, is also critical to successfully executing systematic maintenance initiatives. The speakers for this presentation will discuss the importance of preventive maintenance and how it can be successfully conducted. Both have extensive experience as traffic operations managers with older medium-sized cities and have been involved members of professional organizations concerned with traffic operations and maintenance.

MAINTENANCE OF ROADWAYS AND ROADSIDES

Are Demonstration Projects Worthwhile?

Two Successful Case Histories: Geosynthetically Reinforced Soil Walls and Ballistic Soil Nails for Shallow Roadside Slope Failures

ROBERT BARRETT
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BRYAN WAVRA
Soil Nail Launcher

This presentation documents two technologies ideally suited for shallow roadside slope failures that were initially evaluated through demonstration and field trial projects: (1) geosynthetically reinforced soil walls and (2) ballistic soil nails. These technologies, developed through university and agency research and development, have been implemented on a daily basis for mitigation of shallow roadside slope failures throughout the United States. Field demonstrations and trials were key steps in the development of these technologies. Project examples illustrating the economy and speed of these technologies over traditional methods will be presented. Mathematical models describing the performance of geotechnical technologies often lag performance observed through full-scale testing. This is primarily a function of the variability of soils and conditions encountered in the field. The interaction between nonuniform soils, variable field conditions, and structural elements used for reinforcement has proven the need for full-scale demonstration projects that evaluate the performance as composite structures. The behavior of these soil–structure composites has been replicated throughout the initial research and now as regularly used stabilization techniques for shallow roadside slope failure. Of particular importance is the continued field trials and implementation of new technologies based on their observed performance, even if a thorough mathematical understanding has not been accomplished. The first part of the presentation will focus on the initial research of fabric reinforced walls by Professor J. R. Bell at Oregon State University and instrumented field demonstration walls built by the U.S. Forest Service (USFS) and Colorado Department of Transportation in the 1970s.These field demonstrations showed that the fabric (geosynthetically reinforced) walls were much stronger than indicated by the laboratory models. Recent full-scale load tests by the FHWA have confirmed the high-load capacity of the geosynthetically reinforced walls using closely spaced geosynthetic layers. The second part of the presentation will provide background on the development of ballistic soil nails for shallow roadside slope repair. Developed in Europe in the late 1980s to repair shallow landslides and severe erosion problems at a fraction of the time, cost, and environmental impact of traditional repair techniques, the technology was never successfully commercialized in Europe and only recently gained momentum in the United States. A demonstration project sponsored by FHWA and the USFS evaluated the capabilities of the soil nail launcher to stabilize shallow roadside failures at eight sites in four states in 1992. The original success of this demonstration project eventually led to commercialization of the ballistic nail launcher in the United States in 2002 and a multitude of successful installations in America. The use of launched nails has expanded to New Zealand, Canada, and Australia. The presentation will concluded with project examples illustrating the successful implementation of each technology for roadside slope repair. The use of ballistic soil nails for slope and foundation support combined with the construction of geosynthetically reinforced soil walls will be shown as a swift, economical alternative to traditional sheet pile walls or tieback soldier pile walls.

APPENDIX

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