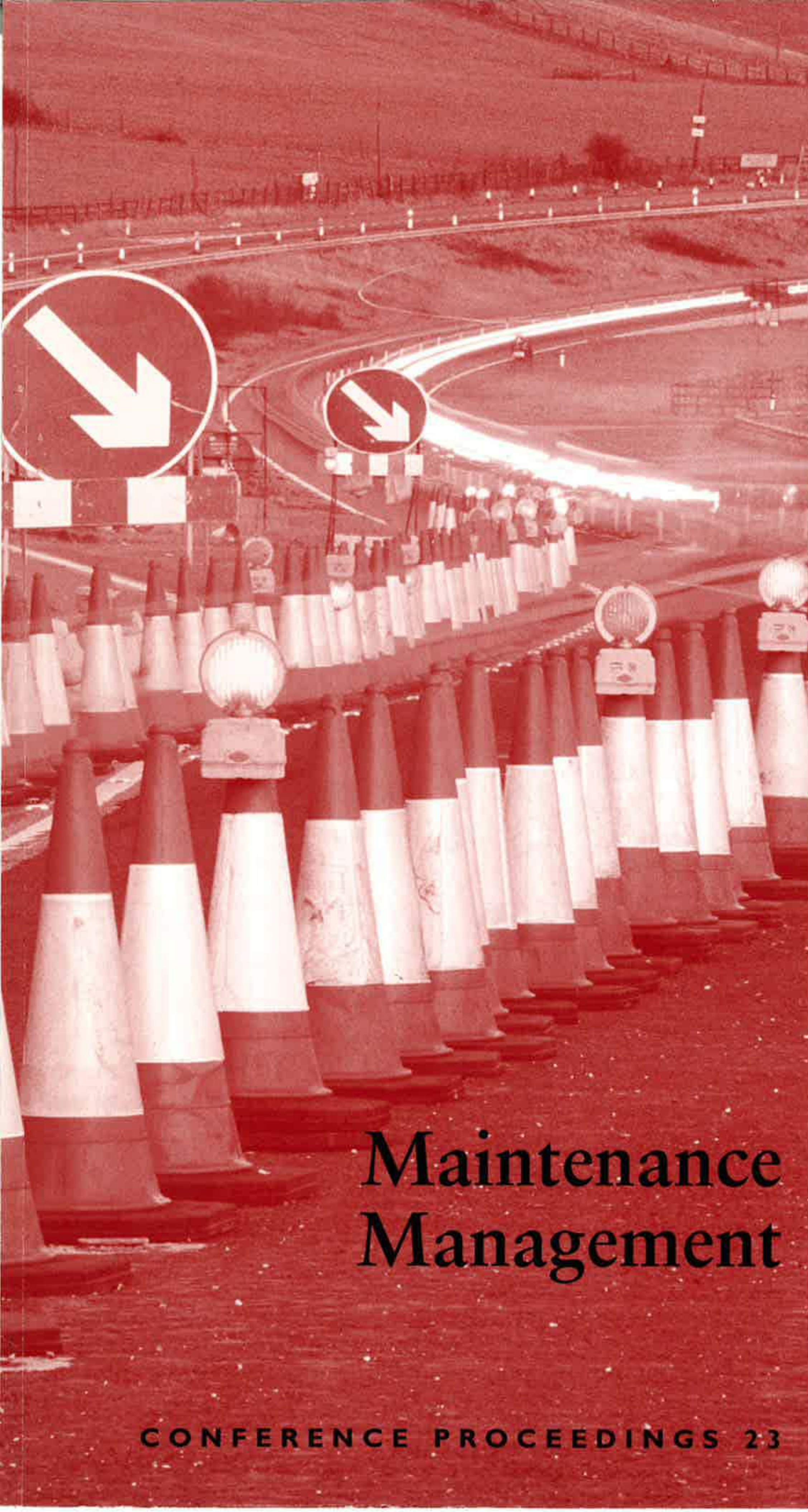

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Contents

Foreword

This proceedings contains papers presented at the Ninth Maintenance Management Conference of the American Association of State Highway and Transportation Officials (AASHTO) and the Transportation Research Board (TRB) held in Juneau, Alaska, July 16–20, 2000. AASHTO's Highway Subcommittee on Maintenance and TRB's Section on Maintenance organize and conduct conferences every 3 to 4 years to provide professionals responsible for maintaining highways with information on the state of the art in maintenance operations and management. Areas addressed include management, safety, pavements, structures, roadside, snow and ice control, equipment, research, and environmental concerns. The conference was conducted in cooperation with the Federal Highway Administration, the Alaska Department of Transportation and Public Facilities, and the Iowa Department of Transportation.

Part 1
PAVEMENT MAINTENANCE

Pavement Maintenance
Preparing for the 21st Century

James S. Moulthrop and R. Gary Hicks

The current state of practice with regard to pavement preservation and some of the challenges facing the pavement maintenance industry in the 21st century have been studied. Pavement preservation (including preventive maintenance) needs to be adopted as an essential program element in agencies so that the U.S. highway system can be properly maintained at the levels expected and demanded by users. Some of the issues and challenges for both rigid and flexible pavements have been addressed.

Highway agencies throughout the world face increasing demands and decreasing resources to maintain and preserve their highway networks. The demand to "do more with less" has become an operating slogan for many of these agencies. Historically, the emphasis has been on constructing new facilities; however, most are currently in the maintenance or preservation mode, a trend that can be expected to continue in the foreseeable future.

According to recent figures reported by the FHWA, the condition of the highway pavements on the national highway system is such that the cost to maintain the system at its existing condition level is nearly $50 billion annually (*1*). The United States is currently spending over $25 billion/year and cost estimates to bring the entire system up from its current level to a "good" level exceed $200 billion. Judging from this, it is clear that current efforts cannot continue using the traditional approaches to managing pavement maintenance and that the pavement preservation strategies employed by the various levels of departments of transportation (state, county, city) need to be restructured.

The purpose of this paper is twofold:

- Present the current state of practice on pavement preservation, including some of the barriers facing the industry; and
- Discuss the challenges or needs for the industry to ensure quality pavement preservation practices into the 21st century.

Pavement preservation is at the core of all future highway programs. It represents a compilation of activities that provide highway users with a higher level of quality and improved cost-effective service. It is directed at preserving the investment in our highway system, extending pavement life and meeting the needs of the users. It is the sum of all activities undertaken to provide and maintain serviceable highways through the timely application of carefully selected surface treatments to maintain or extend a pavement's life.

Current State of Practice

Pavement maintenance practices currently used by agencies in the United States and throughout the world have evolved with little significant research concerning the numerous maintenance techniques or management meth-

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ods. In contrast, strides have been taken in materials research with developments such as polymer-modified binders for both asphalt and portland cement concrete pavements. This is in part because maintenance historically has taken a backseat to the design and construction of new facilities. During the Strategic Highway Research Program (SHRP) some work was done to improve both sealing and patching techniques. Only recently have agencies begun to invest research and development money into new techniques and practices for maintaining and preserving road systems. Some of the recent efforts are presented in Table 1.

In this section the current state of practice in pavement maintenance treatments, treatment selection procedures, performance of the treatments, and other related factors are described.

TABLE 1 Recent National Research and Development Efforts Dealing with Pavement Preservation

Item	Comments
Formation of FPP (Formerly FPRMR)	• Founded in 1992 to initiate research and training efforts in pavement preservation • Board of Directors composed of representatives from industry, user agencies, and academia • Sponsored a recent study "Selecting a Preventive Maintenance Treatment for Flexible Pavements"
FHWA workshops, training courses on preventive maintenance	• In 1997 established ETG to provide guidelines and technical assistance • Forum for the Future, October 1998 • Pavement Preservation: The Concept of Preventive Maintenance (Released December 1999) • Pavement Preservation: Selecting Pavements for Preventive Maintenance (under contract) • Pavement Preservation: Design and Construction of Quality PM Treatments (future project) • Pavement Preservation: Integrating PM into Pavement Management Systems (future project)
NCHRP studies	• 14-14, Optimum Timing of Maintenance Treatment • 20-50(02), Relative Performance of Jointed Plain Concrete Pavements with Sealed and Unsealed Joints • 20-50(03), Effectiveness of Maintenance and Rehabilitation Options
AASHTO	• Pooled fund study titled "Microsurfacing Mix Design Procedure" • Developed Lead States Team on Pavement Preservation
Innovative Pavement Research Foundation (IPRF)	• Founded in 1998 to foster research and innovation focused on preserving, rehabilitating, and enhancing the existing highway system • Comprised of Industry, State and Federal officials, Academia • Sponsored research of "Best Practices for maintenance and rehabilitation of PCC pavements" • Sponsored research "Influence of Sealing Transverse Contraction Joints on the overall performance of PCC pavements" • Sponsoring synthesis "Cost Effective Restoration Procedures and Optimum Timing for PCC pavements" • Sponsoring research "Effective Repairs of Longitudinal Cracks in PCC pavements" • Sponsoring research for the "Development of a Rolling Wheel Deflectometer"
FHWA/TRB	• National Conference on System Preservation, San Diego, CA (planning underway) • Pavement Preservation Forum #2 (planning just underway)

NOTE: PM = preventive maintenance; PCC = portland cement concrete.

Preservation Treatments

A number of preservation techniques for both flexible and rigid pavements are used worldwide. The most commonly used are indicated in Table 2. Agencies specify the treatment to be used based on their knowledge of the existing pavement distress, anticipated traffic loading, environmental conditions at the project, cost of the treatment, and their experience with the performance history of a particular treatment. Several types of seals for flexible pavements are indicated in Table 2 and the use of some may be restricted to low-traffic-volume facilities because of an agency's prior experience with performance issues when used on pavements with a higher volume of traffic. For example, chip seals are often restricted to use on hot-mix asphalt pavements with an average daily traffic count of fewer than 5,000 because cover aggregate loss can damage vehicles. There are exceptions, particularly with advances in the use of polymer-modified binders for this technique.

Treatment Selection

Pavement condition data are collected by trained observers or with automated equipment that is capable of measuring a number of different pavement characteristics. Agencies acquire these data with their own forces and evaluate them in pavement management systems or they contract the work to consulting engineers. Some agencies have not developed the ability to share pavement management data among their divisions, and as a result decisions about specific treatments are made without adequate information.

A number of factors are generally considered by agencies in selecting a pavement maintenance treatment including the following (*2–4*):

- Surface type and extent of distress,
- Traffic type and volume,
- Climate,
- Expected life,
- Cost-effectiveness of treatment,
- Time of year of placement,
- Availability of qualified contractors and quality materials, and
- Facility downtime (user delays).

A procedure, or policy, is usually established by an agency in order to choose the appropriate treatment and this may include guidelines, goals, and strategies. Current practice is quite variable and ranges from choosing the treatment based on past experience to using comprehensive computer programs that incorporate data analysis and modeling procedures. For example, if permanent deformation in a flexible pavement is determined to be the primary distress and it is confined to the surface layer, some treatments would be better suited to match this distress than others—for example, microsurfacing or thin hot-mix asphalt overlays instead of fog seal or surface dressing. For rigid pavements, treatment selection is determined primarily by the type and extent of distress. For example, joint faulting is often addressed by grinding or by using dowel bar retrofit, although several agencies in the United States have used this technique as a preventive maintenance treatment on undoweled pavements in advance of joint faulting. Cracks in the slab can be maintained for a short time by using crack sealants, whereas longer term solutions may incorporate cross-stitching or dowel bar retrofit.

Performance of Pavement Maintenance Treatments

The performance of maintenance treatments is difficult to assess because the same treatment can be used under

TABLE 2 Current Preservation Treatments Used for Flexible and Rigid Pavements

Flexible Pavements	Rigid Pavements
• Crack sealing	• Joint and crack sealing
• Profile milling	• Joint and spall repairs
• Fog seals	• Longitudinal crack and joint repair
• Sandwich seals	• Dowel bar retrofit
• Sand seals	• Diamond grinding
• Surface dressing (chip seals)	• Full and partial depth repair
• Slurry seals	• Thin PCC resurfacing
• Microsurfacings	
• Cape seals	
• Thin and ultra thin hot mix asphalt overlays	

Note: PCC = portland cement concrete.

TABLE 3 Typical Lifetimes for Various Flexible Maintenance Treatments: Flexible Pavements (*5*)

Treatment	Range of Expected Life, Years
Crack Treatments	2 to 3
Fog Seals	3 to 4
Slurry Seals	4 to 6
Microsurfacings	5 to 7
Chip Seals	4 to 6
Thin HMA	2 to 12

NOTE: HMA = hot-mix asphalt.

a variety of pavement conditions. For instance, a chip seal can be used as a preventive maintenance treatment on a flexible pavement in good condition or as a stop-gap maintenance treatment on a flexible pavement in poor condition. In the case of diamond grinding, the performance of this treatment is highly dependent on the quality and type of aggregates in the existing pavement. In 1996, the Portland Cement Association sponsored a research study on the longevity and performance of diamond-ground pavements, performed by ERES Consultants. Although many questions were answered, some were not, and more research is warranted. Geoffroy (*5*, *6*) noted that a number of factors can affect the performance of maintenance treatments and he provided the performance expectations of various treatments as reported by a number of agencies. Typical lifetimes for the various treatments are presented in Tables 3 and 4 for flexible and rigid pavements, respectively. However, when the agencies try to use life-cycle cost analysis, the life extension provided by a treatment at a given time is essential information that generally is not readily available.

Cost-Effectiveness Evaluation

A number of different procedures are used to evaluate cost-effectiveness when potential treatments are evaluated (*5*), and this step is fundamental to the process. Some procedures are simple and straightforward; others require significant amounts of input data. Although the techniques follow a logical process, some of the information needed to calculate the cost-effectiveness of the treatment includes cost of treatment, life of treatment, cost of traffic control, user costs during application, maintenance and rehabilitation costs over an analysis period, and user benefits for a specific treatment. Data that can be difficult to obtain include the following:

- Estimated life for the various treatments as a function of the existing pavement condition,
- User delays associated with the various treatments, and
- User benefits associated with the various treatments.

Determining which factors to include in the analysis and developing the evaluation procedures are generally the responsibilities of the specifying agency. Most agencies do not yet perform a cost analysis for maintenance treatments.

TABLE 4 Typical Lifetimes for Various Flexible Maintenance Treatments: Rigid Pavements (*3*, *4*)

Treatment	Range of Expected Life, Years
Joint and Crack Sealing	2-10[a]
Diamond Grinding	10-20[b]
Dowel Bar Retrofit	10-15[c]
Full and Partial Depth Repair	10-15
Thin PCC Resurfacing	15-25

NOTE: PCC = portland cement concrete.

[a] Depending on the type of joint sealant used, life can range from 2-10 years; 2 years for bituminous-based materials, 4-6 for polymer modified bituminous materials, and 8-10 years for silicon materials.

[b] The ERES study indicated that the average life of diamond grinding is dependent on environmental and loading factors.

[c] Yet to be determined. Several states have studies under way.

Mix-Design Procedures

Standardized mix-design procedures for many of the asphalt treatments presented in Table 2 are available and published by AASHTO, the American Society of Testing and Materials, and other worldwide standards organizations. In addition, many agencies and suppliers have developed their own design procedures that are based on local knowledge of materials and procedures. However, mix-design techniques for most pavement maintenance techniques are still considered by many to be more of an art than a science. For some asphalt pavement treatments (fog seals and sand seals), the principal determinant is the condition of the existing pavement, which in turn affects the application rate for the treatment; thus there is no design procedure per se. Similarly, mix-design procedures for full and partial depth repairs in rigid pavements vary widely across the United States with various degrees of performance. Mix-design procedures for a number of pavement maintenance systems still need to be developed if these techniques are to be widely accepted.

Materials Selection

Many flexible pavement maintenance treatments are thin (25 mm or less) and others must bond to the existing materials; thus, the selection of high-quality, compatible aggregates, binder, and other essential ingredients (cement, fly ash) for the treatments is imperative to achieve the anticipated performance. Adequate friction resistance and durability are desired properties for many of these treatments and selecting aggregates that exhibit these features is an important safety consideration. In addition, the use of polymers to modify emulsions, asphalt cements, and portland cement concrete mix designs has generally provided longer pavement lifetimes at a higher initial cost. The cost-effectiveness of the modified binders and chemical admixtures still needs to be quantified.

The materials used to repair and maintain portland cement concrete pavements vary as well. Most agencies have developed materials and techniques to suit their individual needs. A major effort has been identified to consolidate the available information documenting the best practices for design and materials selection so that maintenance-free service for up to 20 years can be achieved that allows for rapid repair and restoration.

Mixture Evaluation

The tests used to evaluate most maintenance treatments cannot be used to predict the performance of those treatments. For maintenance treatments to be more widely accepted, performance tests that evaluate the benefits imparted by the treatment need to be developed. This is true for both flexible and rigid pavement maintenance treatments.

Construction Procedures

Although most of the construction procedures in pavement maintenance activities have remained essentially the same for a number of years, there have been notable advances in the use of automation to control pavement smoothness, material application rates, proportioning of materials in mix plants, patching machines, and other uses, and this has become standard practice in many agencies. As a result of studies conducted during the SHRP, significant improvements in some treatment application procedures (crack sealing techniques, pothole patching techniques, and equipment) have taken place and implementation has been widespread.

Specifications

Materials and method specifications predominate in the pavement maintenance field, but a number of agencies, in the United States and elsewhere, have developed performance-based specifications while others are using end-result specifications with warranties (*7*). Much of the emphasis for this development is due to the move to have more pavement maintenance work performed by private contractors and less done by department forces. In addition, some agencies have privatized total maintenance (right-of-way to right-of-way) of portions of their systems by contracting maintenance to firms for 5 years or more.

Funding for Maintenance

Most agencies have not been able to rely on dedicated funding for pavement maintenance. This makes it difficult to plan for preventive maintenance and pavement preservation activities. Part of the problem is associated with making the paradigm shift from worst first to a preventive maintenance or pavement preservation approach. Administrators and legislators need to be taught about the importance of preventive maintenance with examples that relate to them directly (maintenance of vehicles or homes) before they commit money to pavement maintenance.

Challenges for the Future

As the pavement maintenance community moves into the 21st century, a number of significant issues must be addressed. Many agencies worldwide are faced with the daunting task of managing pavement assets with reduced staff and shrinking budgets. At the FHWA Forum for the Future (*8*), sponsored by a number of public and private sector groups and held in late 1998, a group of practitioners set out to develop a roadmap for the future in order to develop strategies in pavement maintenance procedures that will result in greater safety, convenience, and customer satisfaction to the traveling public. The major issues identified in the forum (plus others) are discussed here. Similarly, the portland cement concrete industry laid out a blueprint for portland cement concrete pavement research (*9*) that included work on maintenance and rehabilitation. These are also addressed here.

Better Understanding of Pavement Preservation and Preventive Maintenance

Because of limited resources, the move toward preserving our pavements by providing the "right treatment, to the right road, at the right time" is a concept that must be adopted if agencies are going to minimize costs while meeting customer expectations. Agencies must do a better job of defining the benefits of preservation programs and preventive maintenance techniques. This concept must be communicated to the customer—that is, the traveling public. Pavement preservation is an inclusive term and considers all the "activities undertaken to provide and maintain serviceable roadways"(*5*); this includes corrective and preventive maintenance as well as some rehabilitation. Preventive maintenance as defined by AASHTO's Subcommittee on Maintenance "is the planned strategy of cost-effective treatments to an existing roadway system and its appurtenances that preserves the system, retards future deterioration, and maintains or improves the functional condition of the system without substantially increasing structural capacity." Simply put, pavement preservation is a global term relating to protecting and preserving the pavement assets in place by using a number of different strategies that may include structural improvement to address those pavements that are structurally deficient, while preventive maintenance is keeping good roads in good condition (*10*). Without a basic understanding of these approaches, few agencies will be able to garner support for pavement preservation and preventive maintenance programs from the traveling public, contracting industry, and legislative representatives. Current trends in a number of states indicate that pavement preservation concepts are being endorsed and implemented. The AASHTO Pavement Preservation Lead State Team confirmed this with a recent survey.

Eliminating Art and Introducing Science

As mentioned previously, many perceive the mix-design and evaluation process for maintenance techniques to be "black magic." Current mix-design procedures do not use measures of basic material properties that can be used to predict performance. As a result, only experienced material suppliers and contractors using their knowledge base are able to generate products that consistently perform well. Even in these instances, it may not be possible to transfer this knowledge into other regions without considerable development work. Performance-related testing is vital to ensuring quality products in all parts of the United States and the world. Considerable research is needed to develop performance-based mix-design procedures and specifications.

Integrating Pavement Performance Data

Data on the benefits or effectiveness (life or improved life) of pavement maintenance treatments are sorely lacking. Although data may be collected by a number of different methods within an agency, documentation is sparse, data may not be transferable, and often the data are not analyzed in an organized fashion. Performance data for each treatment are essential if an agency wants to make decisions about the most cost-effective treatment to apply.

Integration of various management systems that currently exist (pavement management, maintenance management, project management) is necessary for effectively managing pavement information that can lead to improved pavement maintenance planning, programming, and scheduling. Integration of management systems is under way in some agencies but more is needed, and this is impeding the advancement of pavement preservation. There is an urgent need to develop performance models that clearly show the impacts of the various maintenance treatments.

Need for Dedicated Funding

Funds for pavement maintenance are often allocated based on money that is left over after funds for all other programs are committed. In addition, if a natural disaster occurs, funds for cleanup and restoration of services are often taken directly from the pavement maintenance budget, which reduces the amount available for preventive maintenance activities. To maintain a pavement system to meet customer demands and expectations, funding must be dedicated to these preventive maintenance and pavement preservation activities so that planning, programming, and scheduling can be performed in order to do the "right treatment at the right time." Educating legislators and customers about the needs for dedicated funding for pavement preservation including preventive maintenance is an essential element of an effective pavement preservation program.

Of all the program needs in the pavement preservation area, this is most essential. If funds are not available for a sustainable preventive maintenance program, it is doomed to failure.

Performance Specifications and Quality Assurance

In light of the downsizing of agencies, emphasis on performance-based specifications and quality assurance, including training, is essential for improved strategies. New ideas specific to pavement maintenance activities must be considered in order to advance the technologies needed to meet customer demands. Although there have already been efforts to develop performance specifications, a much broader range of materials and processes used in pavement maintenance activities should be included. With few exceptions, only hot-mix asphalt and portland cement concrete specifications have been advanced in the past 20 years or more. Quality assurance in pavement maintenance activities is in the same predicament or at the same low level of advancement and use as performance specifications. A few agencies have adopted quality assurance for maintenance but much remains to be done. As more agencies change from using agency maintenance forces to contract maintenance, better specifications and quality assurance become more important (*7*).

Downsizing, new contract employees, and job changes all affect the ability to keep a well-trained workforce. The change from agency maintenance forces to contract maintenance requires that remaining department personnel change from maintenance "doers" to contract managers, which requires different skills. Some training programs targeted to enhance these skills are currently being developed by the National Highway Institute but additional training programs are needed and the existing programs need to be updated.

Research and Training

Although advances in materials and techniques for pavement maintenance have occurred, more research and training are essential in the areas of policy development for effective management of pavement maintenance, mix designs, specification development, cost-effectiveness of treatments, and the best application timing of various treatments. Immediate research and training needs are noted below.

Mix Design

Research to develop better and more comprehensive mix-design procedures that are based on basic material properties are related to performance and can be used in the quality assurance process as needed for most pavement maintenance techniques. Procedures to evaluate thin treatments of various types must be developed with sound engineering principles.

Materials Selection

Aggregate specifications for pavement maintenance treatments need to be evaluated. Often the materials specified follow standard construction specifications; however, during the placing of thinner courses in maintenance, as previously noted, more durable aggregates may be required to obtain expected performance. Many of the maintenance treatments are constructed with emulsified asphalt cements, and the compatibility of the aggregate to the emulsion becomes vitally important in some material mixtures. When materials are used in patching, they must bond to the existing pavement layer materials and perform as a part of the existing material. Often they also must be exposed to traffic shortly after installation. These types of specialized requirements need to be considered in the selection and specifications of maintenance materials.

New Technologies

Continued efforts are needed (by industry) to develop improved technologies that improve performance or are most cost-effective. Many of the new technologies come from Europe (or elsewhere) where agencies and industry work in partnership to do their jobs better. This same sort of partnership activity is needed in the United States.

Timing of Pavement Maintenance Treatments

Although SHRP research in determining the best time to apply various maintenance treatments to obtain the greatest return on the funds expended was begun, much analysis of the existing data is needed, and the SHRP studies need to be followed through to conclusion. Additional studies should be undertaken to determine the correct timing for placing pavement maintenance treatments in localized environmental conditions with locally available materials. As noted previously (Table 1), an NCHRP study to determine the optimal timing of maintenance treatments has recently been initiated.

Construction Practices

Maintenance activities are much more time dependent than construction, and the development of equipment and methods that facilitate the application of maintenance treatments in a timely manner while providing the desired quality level needs to be undertaken. Although SHRP studied some aspects of pavement maintenance techniques and equipment, much remains to be done. There is a need to expand on simplified practices for maintenance-type activities, such as those developed by the Kansas Department of Transportation (*11*).

Specifications

As noted previously, some work in this area has been done but different approaches need to be explored for maintenance activities. Simply adopting construction specifications in the maintenance area is not appropriate in most instances. Research in performance-based specifications and end-result specifications with warranties for maintenance activities is sorely needed.

Performance of Pavement Maintenance Techniques

The industry must begin to develop comprehensive techniques to document the performance characteristics of the various pavement maintenance procedures that can be used to predict performance. Although the performance of some maintenance treatments was investigated in the SHRP studies, additional studies need to be completed with other treatments, locally available materials, and performance-based mix designs to provide the performance information needed to permit incorporation of pavement maintenance treatments into pavement management systems. If agencies cannot explicitly demonstrate to their customers that their pavement preservation strategy is cost-effective and provides a safe, smooth, roadway, they will not obtain the support to continue this type of program.

Urban Maintenance Issues

A major challenge in the next century is finding new and improved ways to maintain roadways in urban areas without causing undue delays or hardships to users. Increased nighttime work is needed, and techniques that allow maintenance to be accomplished more quickly and under normal traffic conditions must be found.

SUMMARY

Information has been presented about the current state of practice with regard to pavement maintenance as well as some of the challenges facing the industry for the 21st century. Pavement maintenance (or preservation) needs to be elevated in stature so that highway systems can be kept at a level demanded by the users.

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Performance-Based Mix-Design Method for Cold In-Place Recycling of Bituminous Pavements for Maintenance Management

K. Wayne Lee, Todd E. Brayton, David Gress, and Jason Harrington

The high cost and environmental impact of pavement rehabilitation have led to an increase in the use of cold in-place recycling (CIR) as an effective alternative to other rehabilitation strategies. However, currently there is not a universally accepted or standard mix design for CIR. This project is being undertaken with the objective of developing a performance-based mix-design procedure for CIR through laboratory evaluation and limited field verification. This project focuses on partial-depth CIR with asphalt emulsions as the recycling agent. After modified Marshall mix design recommended by AASHTO Task Force 38 was evaluated, a Superpave gyratory compactor and technology were used to develop a volumetric mix design. This requires specimens to be prepared at densities similar to those found in the field. It also suggests that specimens should be cured at 60°C (140°F) for 24 h. This allows for the most consistent specimens and most effectively utilizes the time of laboratory personnel. It is also recommended that the resilient modulus of specimens prepared with the new mix design be used for pavement structural design.

As early as 1915, pavement materials were recycled for road rehabilitation. However, pavement recycling has greatly increased since the mid-1970s, largely because of the oil embargo but also because of a decrease in the availability of good quality aggregates. Several benefits arise from pavement recycling including conservation of materials and energy, preservation of the environment, and reduction in cost. Because of these benefits, many agencies such as the FHWA and state highway agencies began to promote recycling (*1*).

This paper focuses on cold in-place recycling (CIR). CIR projects have been performed successfully since the early 1980s in states such as Kansas (*2*), Oregon (*3*), California (*4*), and New Mexico (*5*). However, some projects have not performed as well as expected. This may be due to the wide variation in mix-design procedures, tests, and criteria. This suggests that a standard mix design should be developed in order to obtain more consistent results in the field as well as to promote the technology. In response to the above need, AASHTO, the American Road and Transportation Builders Association, and the Associated General Contractors of America formed Special Joint Task Force 38. The group produced guidelines for CIR design, but they could not develop a mix design based on performance (*6*). Therefore, a research project has been undertaken in order to develop a performance-based mix design that can be used as a standard for the CIR industry.

CIR Process

There are two methods of cold recycling: CIR and cold central plant recycling. CIR is generally preferable because trucking is reduced, which saves time, money, energy, and

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the environment. The CIR process is completed on grade and typically consists of milling the existing pavement to a specified depth (usually 50 to 100 mm), screening and crushing the reclaimed asphalt pavement (RAP) to meet specifications (typically 25 to 37.5 mm), mixing the RAP with the additives (emulsions, recycling agents, fly ash/cements, lime slurry), and spreading and compacting the mixture. CIR can be accomplished with a single-unit train or a multiunit train. The single-unit train consists of a milling machine that does the cutting, RAP sizing, and blending at the cutting head (*7*). The recycled mix is then placed either in a windrow or directly into a paver hopper. The multiunit train consists of a milling machine, a trailer-mounted screening/crushing unit, and a trailer-mounted pugmill mixer.

A conventional asphalt paver is usually used to place the recycled mixture (typically 50 to 100 mm thick). After placement, compaction starts once the emulsion breaks. Breaking is the point at which the color of the mix changes from brown to black. Compaction is then performed first by a large 20.87-Mg (23-ton) pneumatic-tired roller and then by a 9.98-Mg (11-ton) steel double-drum vibratory roller. A new surface course is placed on the CIR mixture after curing for 1 to 2 weeks. This surface course is usually a hot-mix asphalt (HMA) overlay, but it can also be a surface treatment such as a chip seal for roads with a lower volume of traffic.

Weather is a limiting factor on CIR mixes. The minimum air temperature is specified in the range from 10°C to 16°C (50°F to 60°F). In addition, CIR should not be done in the presence of rain or fog.

Absolutely the most important aspect to consider for successful CIR mixtures is project selection. Many of the failed CIR projects were caused by improper project selection. The selection process should include assessing the existing pavement conditions; sampling and testing pavement materials, including the base, subbase, and subgrade; and studying the pavement's history and traffic (*6*).

Most pavement distresses can be successfully corrected with CIR. These include fatigue cracking, transverse thermal cracking, reflection cracking, and raveling. CIR destroys the existing cracking and produces a crack-free layer for the new surface course. However, not all pavements are good candidates for CIR. Some of the pavement distresses and conditions that are less successfully corrected include the following (*6*):

- Rutted pavements caused by too high asphalt content;
- Failures caused by a wet, unstable base, subbase, or subgrade;
- Failures caused by heaving or swelling in underlying soils;
- Stripped pavements;
- Presence of numerous manhole or drainage outlets;
- Excessive steep grades (5 percent and 760 m), which reduce production;
- Heavily shaded areas, which increase curing times and need to be considered during design;
- Asphalt pavements less than 50 mm (2 in.); and
- Excessive roadway accesses such as driveways.

Other factors need to be considered when the decision to use CIR is being made, such as project size, pavement width, traffic volumes, and congestion.

An Internet website has been developed with the purpose of being a central focus area for CIR technology that can be easily accessed by individuals interested in CIR (*8*).

Experimental Work Plan

Because of limited funds and limited time, the mix-design will be developed for partial-depth CIR, which is defined as a rehabilitation technique that reuses a portion of the existing asphalt-bound materials (*1*). In addition, it was decided that the additive to be evaluated would be limited to asphalt emulsions with the Superpave gyratory compactor (SGC) being used for the volumetric mix design.

A work plan has been formulated for the experimental work of developing a mix design, and it consists of five phases. The first is identification of sensitivities for CIR mixtures. The important distress modes to consider in the mix design are rutting, fatigue cracking, thermal cracking, and water sensitivity. The second phase is procurement of the test samples, including the RAP and emulsions. To have representative samples, the RAP needed to be obtained from different regions. The three places where RAP was obtained were Kansas, Connecticut, and Ontario. For the third phase of the work plan, the modified Marshall mix-design method recommended by AASHTO Task Force 38 is evaluated. The fourth phase is development of a new performance-based mix-design method. The final phase is a limited field evaluation.

Evaluation of Modified Marshall Mix Design

The modified Marshall mix design, recommended by AASHTO Task Force 38, was evaluated with two RAP samples. The first RAP was from Kansas and used a CSS-1h asphalt emulsion. The second RAP was from Ontario and used a HF150P asphalt emulsion. The procedure is summarized below. However, for the complete detailed procedure refer to the Task Force 38 report (*6*). The mix design is composed of two parts.

The first part is determination of the optimum emulsion content (OEC) and the second part is determination of the optimum water content (OWC). The steps for the first part are summarized as follows:

- Weigh sufficient RAP to fabricate 62.5-mm (2.5-in.) specimens into individual pans and heat at mixing temperature (25°C) for 1 h. Prepare three specimens for each emulsion content (EC).
- Add sufficient water to obtain 3 percent total liquids content and mix for 1 min.
- Add emulsion heated to 60°C (140°F) and mix until evenly dispersed but less than 2 min.
- Fabricate specimens by applying 50 blows of the Marshall hammer to each face at 25°C (77°F).
- Cure specimens in their molds for 6 h at 60°C.
- Remove molds from the oven and allow specimens to cool on their sides overnight and extrude.
- Test specimens for bulk specific gravity (25°C).
- Bring specimens to 25°C for 2 h and test for stability and flow (AASHTO T245).
- Determine maximum specific gravity for each EC.

Data from the described procedure were used to determine the OEC.

In the second part, three specimens, each with different water contents (WCs) below and above 3 percent, were fabricated at the OEC. A similar procedure was used to determine the OWC.

Table 1 presents the gradation of the Kansas and Ontario RAPs used in this study. Tables 2 and 3 present the tabulated results for parts one and two, respectively.

The OEC for the Kansas RAP was determined to be 1.2 percent based on the highest stability value. The OWC was found to be 3.0 percent based on the highest stability and optimum air voids. The OEC for the Ontario RAP was determined to be 1.2 percent based on the highest stability value. The OWC was found to be 2.2 percent based on the highest stability and optimum air voids. However, there was one noticeable problem with the mixtures. The air voids in the mixes were higher than the design parameter of 9 to 14 percent air voids suggested by AASHTO Task Force 38. One possible reason for this problem is the gradation of the RAP, which has a very small amount of fine material. The coarse RAP does not allow for proper compaction. In addition, CSS-1h is usually best used with dense-graded mixtures.

TABLE 1 RAP Gradation (Processed)

Sieve Size	Kansas RAP % Passing	Ontario RAP % Passing	Connecticut RAP % Passing
37.5 mm	100	100	100
25 mm	100	100	98.4
19.1 mm	90.4	96.1	92.4
12.5 mm	76.1	86.0	82.9
9.5 mm	65.5	74.7	72.2
4.75 mm	42.6	48.3	47.6
2.00 mm	23.3	27.1	28.9
1.18 mm	15.8	12.1	16.3
0.6 mm	8.7	4.1	8.2
0.3 mm	3.5	1.1	3.0
0.15 mm	1.5	0.3	0.8
0.075 mm	0.4	0.1	0.2

TABLE 2 Modified Marshall Mix-Design Data for Cold In-Place Recycling, Mix 1—Varying Emulsion Contents

Kansas RAP w/CSS-1h Emulsion					
Emulsion %	0.5	1.0	1.5	2.0	2.5
Water %	3.0	3.0	3.0	3.0	3.0
Bulk SG	2.042	2.019	2.011	1.991	1.991
Max. SG	2.453	2.444	2.434	2.413	2.405
Air Voids (%)	16.8	17.4	17.4	17.5	17.2
Unit Weight (pcf)	127.1	125.6	125.2	123.9	123.9
Stability (lbs)	1733	1675	1833	1667	1664
Flow (1/100 in.)	12.0	15.0	17.0	19.8	20.7
Ontario RAP w/HF150P Emulsion					
Emulsion %	0.5	1.0	1.5	2.0	2.5
Water %	2.0	2.0	2.0	2.0	2.0
Bulk SG	2.093	2.108	2.092	2.114	2.100
Max. SG	2.469	2.450	2.431	2.417	2.402
Air Voids (%)	15.2	14.0	13.9	12.6	12.6
Unit Weight (pcf)	130.2	131.2	130.2	131.6	130.7
Stability (lbs)	1499	1581	1390	1254	1222
Flow (1/100 in.)	14.5	13	16	11	19

NOTE: 1 lb/ft^3 (pcf) = 16.02 kg/m^3; 1 in. = 2.54 cm; 1 lb = 0.45 kg; SG = specific gravity.

TABLE 3 Modified Marshall Mix-Design Data for Cold In-Place Recycling, Mix 2—Varying Water Contents

Kansas RAP w/CSS-1h Emulsion					
Emulsion %	1.2	1.2	1.2	1.2	1.2
Water %	2.0	2.5	3.0	3.5	4.0
Bulk SG	2.014	2.033	2.038	2.034	2.019
Max. SG	2.415	2.418	2.419	2.418	2.413
Air Voids (%)	16.6	15.9	15.7	15.9	16.3
Unit Weight (pcf)	125.3	126.6	126.9	126.6	125.7
Stability (lbs)	1758	1867	2107	1942	1725
Flow (1/100 in.)	19.7	20.0	17.7	17.3	18.3
Ontario RAP w/HF150P Emulsion					
Emulsion %	1.2	1.2	1.2	1.2	1.2
Water %	1.5	2.0	2.5	3.0	3.5
Bulk SG	2.056	2.061	2.074	2.082	2.078
Max. SG	2.485	2.486	2.483	2.487	2.490
Air Voids (%)	17.3	17.1	16.5	16.3	16.5
Unit Weight (pcf)	128.0	128.3	129.1	129.6	129.4
Stability (lbs)	1378	1274	1300	1300	1144
Flow (1/100 in.)	16.5	15	15	13	10.5

NOTE: 1 lb/ft^3 (pcf) = 16.02 kg/m^3; 1 in. = 2.54 cm; 1 lb = 0.45 kg; SG = specific gravity.

During the evaluation, the following problems and disadvantages were identified with the modified Marshall procedure:

- The first and foremost disadvantage with this procedure is the amount of time needed to perform the entire procedure. The procedure can take more than 8 days to perform. This amount of time may be more than most contractors and department of transportation engineers are willing to allocate for one mix design.
- The procedure does not give any specifications for when new aggregate should be added to the mixture. There should be some specification for the gradation of the mixture, either a general specification or an agency specification.
- The amount of material needed to fabricate 62.5-mm (2.5-in.) specimens was about 1000 g, which was less than that suggested in the procedure (1150 g).
- The procedure does not mention how long to cure the specimen to allow the mixture to break.
- The procedure does not state how long to heat the emulsion in the oven.
- To determine bulk specific gravity, the procedure requires immersing the specimens for 3 to 5 min in the water. However, because of higher air voids found in CIR mixes it may be better to keep the specimens in the water for the full 5 min.
- The procedure does not clearly state how to determine the optimum values for the emulsion and WCs.
- The design has no bearing on how well the mix will perform. The critical need of the industry is to show how the mix performs.

These observations suggest that this procedure may not be the best mix-design method for CIR. In addition, because the Superpave mix design has been successfully used for HMA, it was decided to modify the Superpave mix design for CIR in this project. In the process of developing the performance-based mix-design method, the disadvantages of the modified Marshall mix design would be addressed.

Development of a Performance-Based Mix Design

Pilot Study

A pilot volumetric mix design using the SGC was performed for the Kansas, Ontario, and Connecticut RAPs. The purpose of this pilot study was to determine how the different materials react to compaction of the SGC. The density values obtained from this study will be used to help determine the amount of compaction that will be needed for the remainder of the experimental testing as well as for the development of the new mix design. The modified Marshall mix-design procedure was used for the pilot modified Superpave mix design with some adjustments as follows:

- Weigh 4000 g of RAP into individual pans and heat at mixing temperature (25°C) for 1 h. Heat emulsion and molds at 60°C for 1 h. Prepare two specimens for each EC.
- Add sufficient water to obtain 3 percent total liquids content and mix for 1 min.
- Add emulsion and mix until evenly dispersed but less than 2 min.
- Allow the mixture to cure for 1 h to allow the emulsion to break before compaction.
- Fabricate specimens using the SGC by applying 52 gyrations at 600 kPa at an angle of gyration of 1.25° at 25°C.
- Extrude specimens from the molds and cure for 6 h at 60°C.

- Remove specimens from the oven and allow specimens to cool on their sides overnight.
- Test specimens for bulk specific gravity (25°C).
- Determine maximum specific gravity for each EC.

The data from this procedure were used to determine OEC. At this OEC, two specimens with different WCs below and above 3 percent were fabricated. A similar procedure was used to determine the OWC.

Tables 4 and 5 present the tabulated results for parts one and two of the mix design, respectively. The OEC for the Kansas RAP was determined to be 1.4 percent at air voids of 11 percent. The OWC was found to be 2.9 percent at 11 percent air voids.

The air voids for the Ontario RAP was in the range of 6 to 9 percent, which indicates that the compactive effort was too high. However, the SGC measures the height of each specimen after every gyration, which can be used in conjunction with the measured bulk specific gravity to determine the number of gyrations where the specimens are at the optimum 11 percent air voids. The point where the four various ECs average 11 percent air voids is then taken to be the proper number of gyrations. For this mixture it was determined that 25 gyrations were necessary (Figure 1). Therefore, the OEC for the Ontario RAP was determined to be 1.2 percent and the OWC was found to be 2.1 percent.

The OEC for the Connecticut RAP was determined to be 1.2 percent at the maximum unit weight of 2116.07 kg/m^3 (132.1 lb/ft^3), which resulted in air voids of 13.4 percent (Figure 2*a*). The OWC was found to be 2.3 percent at the maximum unit weight of 2136.9 kg/m^3 (133.4 lb/ft^3), which resulted in air voids of 12.6 percent (Figure 2*b*).

TABLE 4 Modified Superpave Mix-Design Data for Cold In-Place Recycling to Determine OEC

Kansas RAP w/CSS-1h Emulsion				
Emulsion %	0.5	1.0	1.5	2.0
Water %	3.0	3.0	3.0	3.0
Bulk SG	2.157	2.155	2.155	2.141
Max. SG	2.436	2.429	2.422	2.414
Air Voids (%)	11.5	11.3	11.0	11.3
Unit Weight (pcf)	134.2	134.2	134.2	133.2
Ontario RAP w/HF150P Emulsion				
Emulsion %	0.5	1.0	1.5	2.0
Water %	3.0	3.0	3.0	3.0
Bulk SG	2.287	2.307	2.311	2.315
Max. SG	2.506	2.495	2.486	2.479
Air Voids (%)	8.8	7.6	7.0	6.6
Unit Weight (pcf)	142.3	143.6	143.8	144.1
Connecticut RAP w/HF150P Emulsion				
Emulsion %	0.5	1.0	1.5	2.0
Water %	3.0	3.0	3.0	3.0
Bulk SG	2.115	2.127	2.115	2.112
Max. SG	2.462	2.453	2.446	2.434
Air Voids (%)	14.1	13.3	13.5	13.2
Unit Weight (pcf)	131.6	132.4	131.6	131.5

NOTE: 1 lb/ft^3 (pcf) = 16.02 kg/m^3; SG = specific gravity.

TABLE 5 Modified Superpave Mix-Design Data for Cold In-Place Recycling to Determine OWC

Kansas RAP w/CSS-1h Emulsion				
Emulsion %	0.5	1.0	1.5	2.0
Water %	3.0	3.0	3.0	3.0
Bulk SG	2.157	2.155	2.155	2.141
Max. SG	2.436	2.429	2.422	2.414
Air Voids (%)	11.5	11.3	11.0	11.3
Unit Weight (pcf)	134.2	134.2	134.2	133.2
Ontario RAP w/HF150P Emulsion				
Emulsion %	0.5	1.0	1.5	2.0
Water %	3.0	3.0	3.0	3.0
Bulk SG	2.287	2.307	2.311	2.315
Max. SG	2.506	2.495	2.486	2.479
Air Voids (%)	8.8	7.6	7.0	6.6
Unit Weight (pcf)	142.3	143.6	143.8	144.1
Connecticut RAP w/HF150P Emulsion				
Emulsion %	0.5	1.0	1.5	2.0
Water %	3.0	3.0	3.0	3.0
Bulk SG	2.115	2.127	2.115	2.112
Max. SG	2.462	2.453	2.446	2.434
Air Voids (%)	14.1	13.3	13.5	13.2
Unit Weight (pcf)	131.6	132.4	131.6	131.5

NOTE: 1 lb/ft^3 (pcf) = 16.02 kg/m^3; SG = specific gravity.

Experimental Program to Develop New Mix Design

An experimental program was undertaken in order to consider the effects of certain important variables on the CIR mix design. The Connecticut RAP and HFMS-2T emulsion were used for this investigation. Unit weight was the response that was chosen for this analysis, because this is the most important factor to consider for

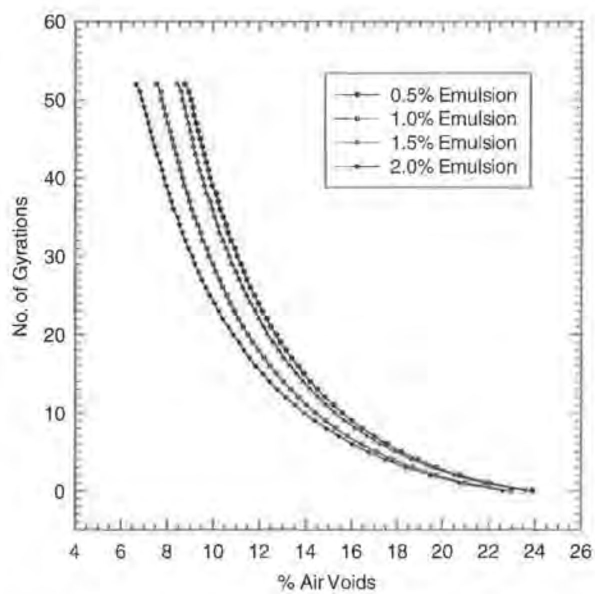

FIGURE 1 Number of gyrations versus percent air voids for Ontario RAP and HF150P at different ECs (3.0 percent WC).

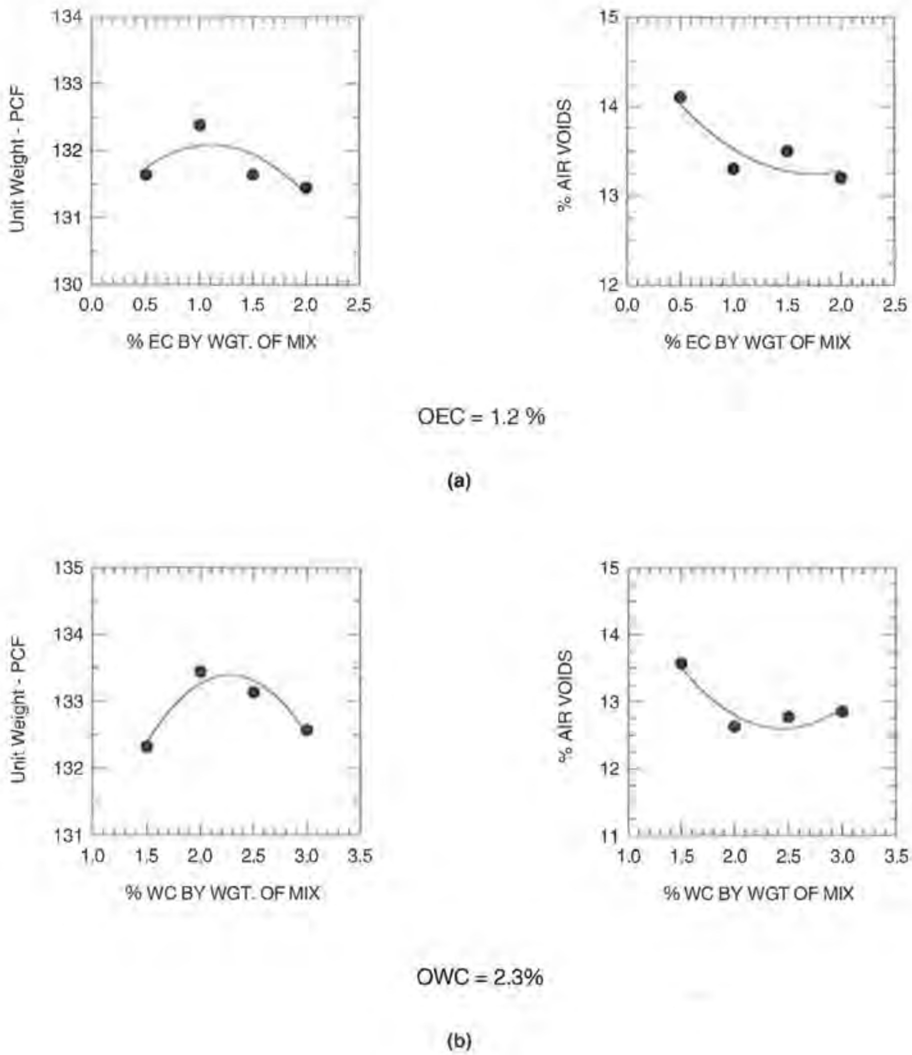

FIGURE 2 Pilot mix design with Connecticut RAP using the SGC: (*a*) different ECs at 3 percent WC; (*b*) different WCs at 1.2 percent EC (1 lb/ft^3 = 16.02 kg/m^3).

new CIR pavements. The variables under study include EC, total liquid content (TLC), curing time, and curing temperature (Table 6). The EC had four levels ranging from 0.5 to 2.0 percent of total mix by weight, in 0.5 percent increments. This range has two ECs above and below the OEC, which was determined in the pilot study. This range also covers most ECs that would be found in the field.

The two levels used for TLC were 3.5 and 4.0 percent. TLC was used as a parameter instead of WC because of its frequent use as a parameter for mix designs. In addition, TLC is a more fundamental measure of the moisture in the mixtures, instead of WC, because the emulsion also contains some water. The TLC of 3.5 percent was chosen because that is the optimum content that was found from the pilot study for the Connecticut material—1.2 percent EC + 2.3 percent WC = 3.5 percent TLC. The TLC of 4.0 percent was chosen because it is a typical field value.

Literature and the results from the questionnaire survey show that there are a wide range of curing times for mix-design specimens, anywhere from 1 h to 3 days. In addition, many mix designs use a combination of curing times and temperatures. Therefore, the curing times of 6 h and 24 h were chosen for this study because these times appear to be the most appropriate for the working schedules of laboratory personnel.

The two most common temperatures for curing specimens after compaction are 60°C and room temperature, which is about 25°C. Furthermore, these temperatures most accurately simulate field conditions; 60°C is a typical value for the highest temperature that pavement reaches during a summer day and 25°C is a typical pavement temperature during summer nights. Therefore, these two temperatures were chosen for the experimental program.

Compaction Level

To investigate the effects of these parameters on CIR mixtures, it was imperative that the densities of the lab-

TABLE 6 Experimental Design: Connecticut RAP with HFMS-2T Emulsion

Curing Temp., F	Curing Time, Hours	Emulsion Content, % 0.5		1.0		1.5		2.0	
	Total Liquid Content, %	3.5	4.0	3.5	4.0	3.5	4.0	3.5	4.0
140	24	2	2	2	2	2	2	2	2
	6	2	2	2	2	2	2	2	2
77	24	2	2	2	2	2	2	2	2
	6	2	2	2	2	2	2	2	2

NOTE: Two specimens were prepared for each cell. 140°F = 60°C; 77°F = 25°C.

oratory specimens simulate field densities. Therefore, actual field densities were obtained from the project that was the source of the RAP. The unit weight that was obtained for the project for the sampling data was 2082.4 kg/m^3 (130 lb/ft^3). Therefore, 2082.4 kg/m^3 was the desired unit weight for the laboratory specimens. To achieve this density, one or more of the parameters of the SGC needed to be changed from the HMA specifications. The possible parameters to change are number of gyrations, vertical compaction pressure, angle of gyration, and speed of gyration. However, a study performed on the SGC at the Asphalt Institute during the Strategic Highway Research Program (*9*) indicated that the speed of gyration has little effect and vertical pressure has only a small effect on density. The angle of gyration was found to have the greatest influence on the density. However, the angle of gyration of 1.25° was shown as the best angle for proper densification (*9*). Therefore, the number of gyrations was chosen as the parameter to change in this study.

The SGC collects the height data of the specimen for each gyration during the compaction process. This information, along with the mass of the mix, can be used to estimate the specific gravity of the specimen after every gyration. This is accomplished by measuring the bulk specific gravity of the compacted specimen and comparing it with the estimated specific gravity after the last gyration. A correction factor, a ratio of the measured to estimated bulk specific gravity, is then applied to the estimated specific gravity to arrive at the corrected specific gravity for each gyration (*10*). This procedure was used on the data gathered from the pilot study, and 37 gyrations were found to achieve a density of 2082.4 kg/m^3 for the Connecticut material. Thus, 37 gyrations were used to compact the specimens for the experimental program.

Test Results and Data Analysis

The bulk specific gravity of each specimen was measured twice. The first measurement took place 2 h after the end of the curing period. The delay was used to allow the specimens heated to 60°C to cool to room temperature. To maintain consistency for all specimens, the specimens that were cured at 25°C were also left for 2 h after the curing period. The second measurement was performed 1 week after compaction to allow all water to leave the specimen.

The unit weight data for the first and the second measurements are presented in Tables 7 and 8. An analysis of variance was performed on these data to investigate the effects of the variables with Minitab statistical software. It was found that all four parameters were statistically significant for the unit weight values that were determined 2 h after curing. A two-sample *t*-test was performed on the values for the two unit weight measurements to determine whether there is a difference between them. Results show that the unit weights just 2 h after curing are higher than the unit weights after 1 week. Closer inspection of the data shows that the largest difference between the two measurements occurs for the specimens that were cured for 6 h and the specimens that were cured at 25°C. The reason for this, as common sense suggests, is that the short time and cooler temperature do not allow all the mixing

TABLE 7 Unit Weights (lb/ft^3) for Experimental Program Using Connecticut RAP with HFMS-2T Emulsion: 2 h After Curing

	Curing Temperature							
	77° F				140° F			
	Curing Time (Hours)							
	24		6		24		6	
	Total Liquid Content (%)							
Emul. Content (%)	3.5	4.0	3.5	4.0	3.5	4.0	3.5	4.0
0.5	132.6	131.9	132.5	130.3	129.9	129.6	132.5	131.3
1.0	129.0	131.6	132.4	133.2	129.8	129.5	131.6	131.2
1.5	131.0	131.8	135.1	135.2	134.4	131.4	130.3	130.4
2.0	131.0	130.6	132.2	131.4	133.6	133.5	132.5	131.4

NOTE: 77°F = 25°C; 140°F = 60°C; 1 lb/ft^3 = 16.02 kg/m^3.

TABLE 8 Unit Weights (lb/ft^3) for Experimental Program Using Connecticut RAP with HFMS-2T Emulsion: 1 Week After Curing

	Curing Temperature							
	77° F				140° F			
	Curing Time (Hours)							
	24		6		24		6	
	Total Liquid Content (%)							
Emul. Content (%)	3.5	4.0	3.5	4.0	3.5	4.0	3.5	4.0
0.5	132.0	130.9	130.2	132.8	130.2	130.1	131.3	130.6
1.0	128.5	130.3	131.1	131.1	129.8	129.7	131.0	131.0
1.5	130.6	130.8	133.6	133.1	134.6	131.6	129.9	130.0
2.0	130.4	129.8	131.7	131.0	133.8	133.8	132.3	131.0

NOTE: 77°F = 25°C; 140°F = 60°C; 1 lb/ft^3 = 16.02 kg/m^3.

water to leave the specimen. One week allows most, if not all, of the water to leave the specimen. The 24-h curing time and the 60°C curing temperature more easily allow the water to be removed from the specimen, which results in less difference between values.

Based on the preceding analysis, the specimen preparation specification has been formulated for the new modified Superpave mix design. The tentative specifications are as follows:

- The specimens would be cured for 24 h at 60°C after compaction.
- A minimum of four ECs would be used.
- The number of gyrations used to compact the specimens should be adjusted to achieve densities similar to those found in the field.

Figure 3 presents the results from the experimental program for the Connecticut material, which was cured for 24 h at 60°C, at 3.5 and 4.0 percent TLC, respectively.

The moisture sensitivity of the mixture will also be evaluated to determine its long-term stripping susceptibility by the use of AASHTO T283.

PERFORMANCE ANALYSIS

CIR mixtures in accordance with the new volumetric mix design will be examined for their performance. The choice of which materials to use depends on the locations for field verification. Currently, plans call for two sites for limited field verification, one in Arizona and the other in Connecticut. The performance of the CIR mixtures prepared for the new mix design will be evaluated. The three distress modes to be investigated for performance analysis will be permanent deformation or rutting, fatigue cracking, and low-temperature cracking.

The performance of the CIR mixtures, in relation to permanent deformation and fatigue cracking, will be predicted by using the computer program VESYS (*11*). To do this analysis, the incremental static dynamic creep test (ISDCT) will be performed to determine the input data.

The ISDCT determines primary properties (creep or elastic compliance) and distress properties (permanent deformation) of 10.16-cm (4-in.) diameter and 20.32-cm (8-in.) high specimens. Because rutting depends on temperature, three different temperatures will be used for the ISDCT.

Creep compliance and the strength-at-low-temperatures test (AASHTO TP9-94) will be performed with the indirect tensile tester (IDT) to evaluate the resistance to low-temperature cracking. The test will be performed at three temperatures for creep compliance: 0°C, −10°C, and −20°C. The tensile strength will be measured at −10°C.

CONCLUSION AND RECOMMENDATIONS

Evaluation of the modified Marshall mix-design method from AASHTO Task Force 38 has suggested that this method may not be the future of CIR mix designs. The expanding use of the Superpave system deems it vitally necessary to provide a mix design for CIR similar to that for HMA with modifications for the nature of cold mixes. Therefore, a volumetric mix design using the SGC has been developed for use with CIR materials.

The next step is to add performance testing—for example, the ISDCT and the Superpave IDT—to this volumetric mix design to complete the performance-based mix design. The final step will be to build test sections for constructibility and testing of on-site performance.

It is also a tentative recommendation that the resilient modulus of specimens prepared with the new performance-based mix design will be used for pavement structural design.

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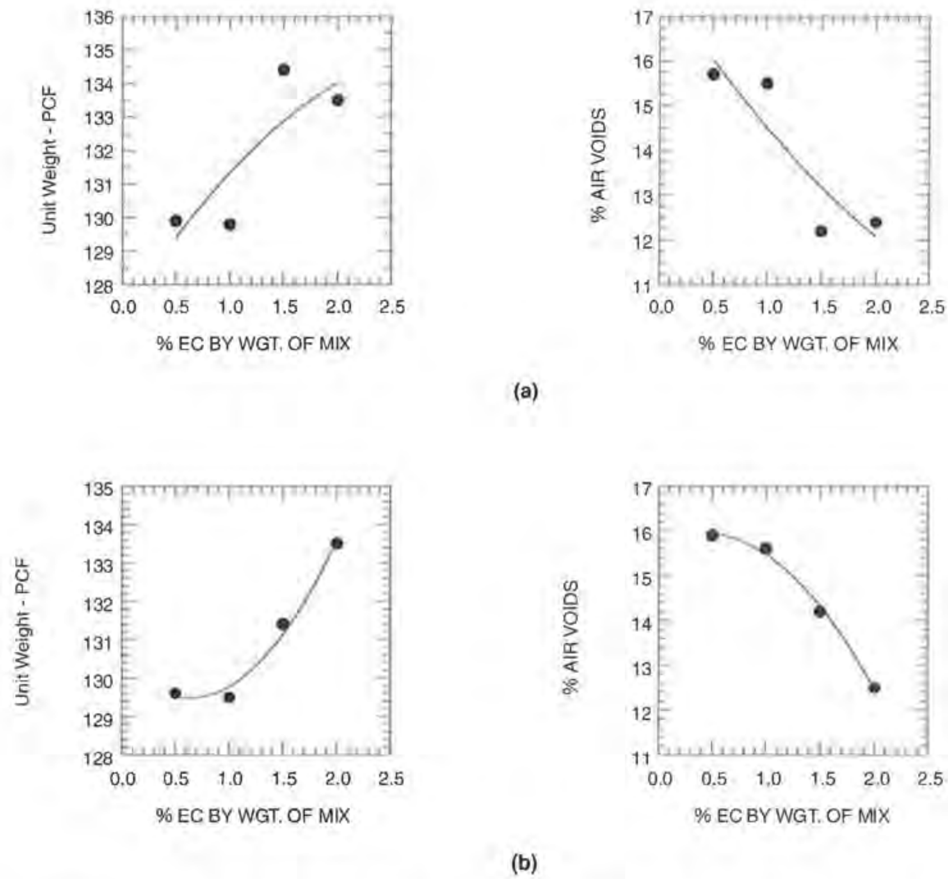

FIGURE 3 Connecticut RAP with 24-h cure at 60°C for the experimental program to develop new mix design: (*a*) TLC = 3.5 percent; (*b*) TLC = 4.0 percent ($1\ lb/ft^3 = 16.02\ kg/m^3$).

make this a successful and useful research endeavor. In addition, the authors thank George Veyera, Milton Huston, and Gail Paolino for their contributions to the research project, and Fred Nashold of the Connecticut Department of Transportation, who supplied field data from the project that was the source of the RAP.

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Rehabilitation Techniques for Stripped Asphalt Pavements in Montana

David R. Johnson and Reed B. Freeman

Asphalt stripping is a fairly common form of distress for pavements in Montana. Currently, the standard technique for rehabilitating these pavements involves the costly removal of most or all of the stripped material before placement of an overlay. The goal of this research is to determine whether the stripped material can remain in place, serving as a structural layer within the rehabilitated pavement. This study has involved the construction of five test sites throughout Montana that have been incorporated into larger overlay projects. At each of these sites, stripped material was removed and replaced from a control section and stripped material was left in place on a test section before placement of an overlay. Only the driving course (chip seal or an open-graded friction course) was removed from the test sections. Background information on the test sites is provided, and the methods (visual, nondestructive testing, and destructive testing) that are being used to monitor the performance of experimental pavement sections are described. Performance results are provided for up to 4 years of service.

The deterioration of asphalt concrete in the form of stripping is caused by separation of asphalt binder from aggregate. This loss of adhesion causes the asphalt concrete to ravel under traffic loads. Stripping occurs in the presence of water, so it is often referred to as moisture damage.

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Currently, the most common method for rehabilitating a stripped pavement in Montana involves removing and replacing most of the stripped material. This practice is expensive because it requires milling and hauling operations in addition to normal paving activities. The Montana Department of Transportation (MDT) initiated this project to investigate the possibility of allowing all stripped material to remain in place. The premise is that the stripped asphalt can retain sufficient integrity to be used effectively within the rehabilitated pavement structure.

Scope of Work

Two methods of rehabilitating stripped asphalt pavements were studied by comparing the performance of full-scale rehabilitated pavement structures. The first method of rehabilitation involved removing and replacing most of the stripped asphalt concrete. Under this approach, the stripped asphalt concrete layer is presumed to have little structural value (less than the value of an equivalent thickness of standard base course material). The second method of rehabilitation required minimal treatment of the in-place stripped asphalt concrete layer. Only existing surface treatments and open-graded friction courses (OGFCs) were removed and then the stripped asphalt concrete layer was overlaid with a new surface course. This approach presumed that the stripped asphalt concrete maintained a structural value at least as high as a standard base course material.

The construction phase of this study began with the identification of five stripped pavements among MDT

Interstate highway resurfacing projects. Plans for each site involved implementing the two rehabilitation methods presented previously. Once sites were identified, historical data were obtained for each site regarding soils information, original structural design, and previous overlays. The condition of the pavements needing rehabilitation was also quantified in general terms.

The five rehabilitated pavement test sections are currently being monitored visually, structurally, and in terms of roughness. Monitoring periods will last for 3 to 5 years. Upon completion of the long-term monitoring phase, the two methods of rehabilitation will be compared economically.

FIGURE 1 Montana test locations.

TEST SITES

Five test sites were selected on Interstate highways across the state of Montana. All the test sites were constructed as part of larger pavement rehabilitation contracts. Test sites were chosen based on the following criteria:

- The sites had to be well distributed across the state,
- Each pavement had to be determined as stripped according to MDT test procedures, and
- The timing for rehabilitation construction had to be appropriate.

The test sites are indicated in Table 1 and their locations are presented in Figure 1. The rehabilitation projects were conducted between 1994 and 1997. The total lengths of the rehabilitation projects ranged from 8 to 27.4 km (5 to 17 mi). Among the chosen test sites, the Rocky Canyon area experiences the most precipitation, and the Lincoln Road–Sieben area experiences the least. The Custer County Line West area experiences the hottest summers. The Tarkio East area experiences relatively mild winters. The five sites rank in the following order in terms of increasing average daily traffic and increasing equivalent single-axle loads: Custer County Line West, Lincoln Road–Sieben, Tarkio East, Bearmouth–Drummond, and Rocky Canyon.

Each test site included one or two test sections and one or two control sections. The control sections employed the remove-and-replace method of rehabilita-

TABLE 1 General Information for Test Sites

Characteristic	Bearmouth-Drummond	Rocky Canyon	Lincoln Road-Sieben	Custer County Line West	Tarkio-East
Project Number	IM 90-3(74) 135	IM 90-6(70) 313	IM 15-4(69) 200	IM 94-4(49) 154	IM 90-1(118) 64
County	Granite	Gallatin	Lewis and Clark	Custer	Mineral
Interstate	I-90	I-90	I-15	I-94	I-90
Length of Project (mi)	15.2	5.3	17.1	8.9	10.5
Date of Rehabilitation	1994–95	1995	1996	1996	1996–97
Climatic Data					
Mean Precipitation (in.)	13.5	18.6	11.4	14.0	14.5
Mean Temperatures[a] (°F)					
7-Day-Average High[b]	91 (3.0)	88 (4.8)	88 (4.8)	97 (4.6)	93 (4.7)
Single-Day Low[b]	−27 (4.2)	−24 (3.4)	−26 (3.1)	−29 (3.8)	−15 (3.5)
Traffic Data					
ADT (Year)	6800 (1991)	8100 (1991)	3700 (1993)	2800 (1991)	4500 (1991)
ADT[c] (Letting Year)	7500 (1993)	9200 (1996)	4000 (1996)	3000 (1993)	5000 (1993)
ADT[c] (Design Year)	13500 (2013)	16500 (2016)	7200 (2016)	4400 (2013)	8600 (2013)
Percent Trucks	20.2	20.3	17.2	20.7	23.8
Average Daily ESALs (over design life)	1090	1590	520	440	900

NOTE: ADT = average daily traffic; ESALs = equivalent single-axle loads; 1 mi = 1.6 km; °C = (°F −32)/1.8.

[a] From SHRP weather database (at least 20 years of data).

[b] Mean (standard deviation).

[c] Projected.

tion, and the test sections incorporated all the existing stripped asphalt concrete into the new structure. The test and control sections are 152.4 to 417.6 m (500 to 1,370) ft long and include both the driving and passing lanes. Locating test and control items adjacent to each other allowed unwanted variables to be minimized by maintaining similarities between

- Existing soil conditions,
- Existing pavement structure dimensions and properties,
- Drainage,
- Horizontal and vertical road geometry, and
- Types and severity of pavement distress.

Information related to previous construction for the test sites is presented in Table 2. The original pavement structures were built between 1964 and 1982. Each original structure included two layers over the subgrade: a crushed aggregate base course and an asphalt concrete surface course. All the reported subgrade types could be expected to provide adequate pavement foundations, without potential for volume changes. Each site had received a single overlay since original construction. The overlays were placed between 1981 and 1985 and each was topped with an OGFC.

Pre-Rehabilitation Evaluations

Before a rehabilitation project, the MDT evaluates the condition of the existing pavement. The nondestructive testing (NDT) team visits the site to evaluate its structural condition and to document their impressions about any visual distress. An additional source of pre-rehabilitation information is the MDT pavement management system, which retains condition data for all state-maintained pavements within Montana. As a supplement for these sources, representatives of Montana State University (MSU) visited the sites and conducted visual inspections specifically for the test sections.

Structural Evaluations

Structural information was obtained with a Road Rater, which provided estimates for the elastic moduli of pavement layers. The reduction of Road Rater data assumes that the pavements consist of multiple layers of linear elastic materials. The reported modulus values, assuming three linear elastic layers for each pavement, are presented in Table 3. These values are conservative estimates for each project because they were obtained by subtracting 0.7 of the calculated standard deviation from the calculated mean. The NDT team impressions on material adequacy, based on estimated moduli, are also presented in Table 3. Surface moduli were lowest at Custer County Line West and were highest at Bearmouth–Drummond, although all were judged to be either adequate or good. Base course moduli were lowest at Lincoln Road–Sieben (judged to be weak) and were highest at Bearmouth–Drummond (judged to be weak). Subgrade moduli were lowest at Bearmouth– Drummond and Tarkio East (both judged to be weak) and were highest at Rocky Canyon (judged to be good). Only two sites had both a base course modulus and a subgrade modulus that were judged to be either weak or marginal: the Lincoln Road–Sieben and the Custer County Line West sites.

Visual Examinations

Visual condition information as obtained from the MDT is presented in Table 4. This information reflects the condition of the entire projects and not just the test sections. All sites were experiencing some degree of raveling of the

TABLE 2 Pre-Rehabilitation Construction Information for Test Sites

Characteristic	Bearmouth-Drummond	Rocky Canyon	Lincoln Road-Sieben	Custer County Line West	Tarkio-East
Original Pavement					
Date of Construction	1971	1964	1964	1971	1982
AC Thickness (ft.)	0.35	0.35	0.50	0.35	0.35
CAB Thickness (ft.)	1.7	2.0	2.4	1.5	1.5
Subgrade Type[a]	A-1-a (GW, GP)	A-2-4 (GM, GS)	A-2-4 (GM, GS)	A-1-b to A-4(0) (SW, SP, SM, ML)	A-1-a to A-3 (GW, GP, SP)
First Overlay					
Date of Construction	1985	1983	1983	1981	1985
AC Thickness (ft.)	0.15	0.30	0.15	0.15	0.15
OGFC (ft.)	0.05	0.05	0.05	0.05	0.05

NOTE: AC = asphalt concrete; CAB = crushed aggregate base; OGFC = open graded friction course (approximately 1/2 in. to 3/4 in. thick); 1 in. = 2.54 cm; 1 ft = 0.3 m.

[a] AASHTO Classification with most probable soil in Unified System shown in parentheses ( ).

TABLE 3 Preconstruction Road Rater Evaluations

Characteristic	Bearmouth-Drummond (westbound)	Bearmouth-Drummond (eastbound)	Rocky Canyon (eastbound)	Lincoln Road-Sieben (northbound)	Custer County Line West (westbound)	Tarkio-East (eastbound)
Date Tested	July 1992	July 1992	July 1991	May 1990	Sept. 1992	Aug. 1992
Location of Tests (Range of Mileposts)	135 to 150	135 to 150	313 to 318	200 to 217	155 to 163	64 to 74
Surface Modulus [a] (psi)	324,000 [Good]	216,000 [Good]	248,000 [Good]	216,000 [Good]	191,000 [Adequate]	233,000 [Good]
Base Modulus [a] (psi)	36,700 [Good]	27,900 [Good]	25,100 [Good]	14,600 [Weak]	21,200 [Marginal]	29,800 [Good]
Subgrade Modulus [a] (psi)	5,090 [Weak]	9,750 [Marginal]	11,900 [Good]	6,670 [Weak]	6,420 [Weak]	5,210 [Weak]

NOTE: Modulus values presented = mean − 0.70 (standard deviation); 1 psi = 6.89 kPa; 1 mi = 1.6 km.

[a]NDT team impression on the quality of material is shown in brackets.

OGFC. Bearmouth–Drummond, Lincoln Road–Sieben, and Tarkio East sites all had transverse cracks. Lincoln Road–Sieben also had longitudinal cracking throughout its length. None of the sites had extensive pothole problems. All sites except Lincoln Road–Sieben had some measurable rutting. All sites had some degree of fatigue cracking; Tarkio East had the most.

Pavement condition information, obtained by MSU specifically for the test sections, generally agreed with the MDT findings. The MSU findings are summarized in the following paragraphs. This section concludes with a characterization of each site in terms of its predominant distress.

At Bearmouth–Drummond, the areas of raveling for the OGFC were about 5 percent for the driving lanes and 9 percent for the passing lanes. Relative to the MDT findings for the entire project, rutting within the test sections did not appear to be as severe. Ruts of 1.27 to 1.9 cm (0.5 to 0.75 in.) were evident in fewer than 5 percent of the wheelpaths. Alligator cracking was also observed in fewer than 5 percent of the wheelpaths. Similar to the MDT findings, transverse cracking was found throughout the test sections; it had progressed to moderate severity in many cases. Longitudinal cracks, generally of low severity, were also found within the test sections.

TABLE 4 Distress Information for Total Project Length

Distress	Bearmouth-Drummond	Rocky Canyon	Lincoln Road-Sieben	Custer County Line West	Tarkio-East
Raveling of OGFC	5% coarse	70% medium to coarse	50% fine	10% coarse	40% coarse
Transverse Cracks	100% 1-3 cracks per 100 ft (< 1/8" to 1/4")	None	100% 5 cracks per 100 ft (1/8" to 1/4")	None	40% 2 cracks per 100 ft (1/8" to 1/4")
Longitudinal Cracks	2% (1/8" to 1/4") centerline	None	100% centerline	None	None
Potholes / Patches	Isolated spots (fair condition)	None	None	< 10% patched (good condition)	None
Ruts	100% (½")	25% (1/2" to 3/4")	None	25% (1/2" to 3/4")	100% (1/2" to 3/4")
Fatigue Cracking	2% initial stage	10% at some stage	> 15% initial stage	20% at some stage	40% initial stage
Date of NDT Team Visit	July 1992	July 1991	May 1990	Sept. 1992	Aug. 1992

NOTE: All percentages indicate percent of total project area or length; 1 in. = 2.54 cm; 1 ft = 0.3 m.

By 1995 when MSU performed a visual condition survey, the alligator cracking at Rocky Canyon had worsened from the time of the MDT inspection in 1991. Alligator cracking, or at least longitudinal cracks in the wheelpaths, were observed along most of the test site. Transverse cracks and longitudinal crack between paving lanes were observed, although they were generally low severity.

A description of the test site at Lincoln Road–Sieben would be similar to that provided by MDT for the entire project. Some slight modifications follow. The longitudinal cracks at centerline were severe for about one-third of the project length. Parallel cracks had formed and raveling had become severe within 0.3 m (1 ft) of the longitudinal crack. Low-severity rutting was also noted to have occurred in the driving lane.

Although cracks were not mentioned at the time of the NDT team visit to Custer County Line West, many transverse cracks had formed within the test site by the year 1995. Moderate-to-high-severity cracks were observed on the order of three per 30.5 m (100 ft) of pavement length. Isolated potholes, both unimproved and patched, were found in the driving lane. The potholes accounted for less than 10 percent of the pavement area. Low-severity rutting was also noted to have occurred in the driving lane.

The condition of the original pavement at the Tarkio East test site was generally poor. Similar to the NDT team report, raveling and alligator cracking were found to be extensive. Ruts were also found in both the driving and passing lanes. Although the MDT had found transverse cracks along the project, they were nearly absent within the test sections. However, the test site did have longitudinal cracking between paving lanes throughout its length. The longitudinal cracks had promoted additional deterioration in the form of small parallel cracks and intermittent potholes.

Distress types found at the various sites are presented in Table 5. Those found by the MDT during their inspections of the entire projects are indicated with a "P." Those found by MSU during their inspections of the test sections are indicated with a "T." Accounting for both MDT and MSU findings, the predominant forms of distress at the various test sites are also presented in Table 5. Bearmouth–Drummond, Lincoln Road–Sieben, and Custer County Line West had extensive transverse cracking and longitudinal cracking. Rocky Canyon and Tarkio East had extensive rutting and fatigue cracking.

Stripping Evaluations

The MDT procedure for evaluating asphalt cores for stripping involves visually inspecting core faces produced by indirect tensile splitting. Cores 10.2 cm (4 in.) in diameter were removed from within the projects included in this study in order to quantify the levels of stripping. If a core disintegrated during removal, this condition was noted. If the core remained intact during removal, the various asphalt concrete layers were separated. The core for each layer was then split along its diameter by indirect tension. Finally, the degree of stripping for each lift was estimated by inspecting the two exposed faces. The MDT procedure uses an integer rating scale, ranging from zero to four, as indicated in Table 6. To minimize subjectivity, the MDT maintains a reference booklet of color photographs showing split core faces, along with their designated ratings.

Results from stripping the inspections are presented in Table 7. Following the MDT approach, all five sites had severe stripping damage. Generally, the overlays received ratings that were similar to or worse than those for the original asphalt surface layer. There were no substantial differences between the driving lanes and the passing lanes. In terms of severity of stripping, the sites grouped are as follows: Custer County Line West and Tarkio East (worst),

TABLE 5 Summarized Distress Information for Entire Projects and Test Sites

Distress	Bearmouth-Drummond	Rocky Canyon	Lincoln Road-Sieben	Custer County Line West	Tarkio-East
Raveling of OGFC	P, T	P, T	P, T	P, T	P, T
Transverse Cracks	P, T	T	P, T	T	P
Longitudinal Cracks	P, T	T	P, T	None	T
Potholes / Patches	P	None	None	P, T	T
Ruts	P, T	P, T	T	P, T	P, T
Fatigue Cracking	P	P, T	P	P	P, T
Predominate Distress for Test Sections	Transverse Cracking	Fatigue Cracking	Transverse and Longitudinal Cracking	Transverse Cracking	Ruts and Fatigue Cracking

NOTE: P – distress observed during MDT inspection of the entire project; T – distress observed during MSU inspection of the test site.

TABLE 6 MDT Rating Scheme for Stripping Damage in Cores

Core Rating	Description
0 (no core)	Asphalt is mostly gone from all sizes of aggregate or the core has disintegrated.
1 (severely stripped)	Most of the aggregate is so clean, the colors of the rock are decipherable.
2 (stripping)	In addition to moisture damage, some large aggregate is not coated.
3 (moisture damaged)	Loss of sheen; dull appearance; some smaller aggregate (minus No. 60 sieve) is uncoated.
4 (good core)	The face is shiny and black. All aggregate particles are coated.

Rocky Canyon and Lincoln Road–Sieben (intermediate), and Bearmouth–Drummond (best).

In addition to using the cores for stripping damage ratings, a few cores were used to obtain estimates of voids and binder content as indicated in Table 7. With the few replicates used in this part of the study, it can be stated only that no substantial oddities or differences were found among the test sites.

Rehabilitation Scenarios

At each site, rehabilitation construction began with milling operations. In the control sections, milling depths ranged from 6.4 to 12.7 cm (2.5 to 5 in.), as indicated in Table 8. Milling was deep enough to remove the existing OGFC and the existing overlay. With the exception of the Tarkio East site, milling in the control section was deep enough to penetrate into the asphalt concrete that was placed as part of the original pavement. In the test sections, milling was used only to remove the OGFC.

Rocky Canyon was the only site that involved stabilization of material before placement of the overlay. After milling of the control section at Rocky Canyon, 24 cm (9.5 in.) of the remaining material was pulverized and stabilized with portland cement. This 24 cm of material included about 8.9 cm (3.5 in.) of asphalt concrete and about 15.2 cm (6 in.) of underlying aggregate base. The test section did not involve any stabilization.

Overlay thicknesses in control sections ranged from 8.9 to 20 cm (3.5 to 8.0 in.), as indicated in Table 8. Overlay thicknesses in test sections ranged from 5.1 to 12.7 cm (2.0 to 5.0 in.) (Table 8). All top lifts of asphalt concrete were modified with polymers. The Bearmouth–Drummond, Lincoln Road–Sieben, and Tarkio East projects all used hot recycling for the lower overlay lifts in the control sections. All asphalt concrete mixtures were MDT Grade D except for the top lift at Custer County Line

TABLE 7 Evaluation of Cores Removed Before Rehabilitation

Characteristic	Bearmouth-Drummond (westbound)	Bearmouth-Drummond (eastbound)	Rocky Canyon	Lincoln Road-Sieben	Custer County Line West	Tarkio-East
Core Stripping Ratings[a]						
Original Surface						
- Driving Lane	2.2 (2-3)	2.0 (2)	1.2 (1-2)	1.8 (1-2)	0.5 (0-2)	1.0 (1-2)
- Passing Lane	2.0 (2)	2.3 (2-3)	1.3 (1-2)	1.7 (1-2)	1.6 (0-3)	0.5 (0-2)
Overlay						
- Driving Lane	1.7 (1-2)	1.2 (0-2)	1.0 (1)	1.3 (1-2)	1.0 (1)	0.6 (0-2)
- Passing Lane	1.8 (1-2)	1.8 (1-2)	1.0 (1)	1.7 (1-2)	0.6 (0-2)	0.2 (0-2)
Number of Cores Evaluated	14	14	12	12	9	32
Additional Core Tests[b]						
Voids Total Mix (%)						
- Original Surface	3.6	3.6	6.1	7.2	3.3	4.0
- Overlay	5.3	6.0	6.6	5.7	7.1	5.4
Binder Content[c] (%)	6.0	5.5	6.1	6.2	5.9	5.5

[a] Mean (range).

[b] Only one test completed for each characteristic.

[c] Bulk mixture containing both the original mixture and the overlay.

TABLE 8 Details of Rehabilitation Construction

Distress	Bearmouth-Drummond	Rocky Canyon	Lincoln Road-Sieben	Custer County Line West	Tarkio-East
Control Section					
Cold Mill,[a] ft (in.)	0.30 (3.5)	0.40 (5.0)	0.25 (3.0)	0.25 (3.0)	0.20 (2.5)
Improved Existing Material[b]		0.80 ft CTPB			
New Material (First Lift)	0.15 ft PMS (hot recycle)	0.40 ft PMS (polymer-mod.)	0.15 ft PMS (hot recycle)	0.25 ft PMS	0.15 ft PMS (hot recycle)
New Material (Top Lift)	0.15 ft PMS (polymer-mod.)		0.15 ft PMS (polymer-mod.)	0.40 ft PMS (polymer-mod.)	0.20 ft PMS (polymer-mod.)
Surface Treatment[c]	Seal & Cover	Seal & Cover	Seal & Cover	Seal & Cover	Seal & Cover
Change in Pavement Thickness, ft (in.)	0.00 (0.0)	0.00 (0.0)	+0.05 (0.5)	+0.40 (5.0)	+0.15 (2.0)
Test Section					
Cold Mill,[d] ft (in.)	0.05 (0.5)	0.05 (0.5)	0.05 (0.5)	0.05 (0.5)	0.05 (0.5)
Overlay	0.15 ft PMS (polymer-mod.)	0.30 ft PMS (polymer-mod.)	0.15 ft PMS (polymer-mod.)	0.40 ft PMS (polymer-mod.)	0.20 ft PMS (polymer-mod.)
Surface Treatment[c]	Seal & Cover	Seal & Cover	Seal & Cover	Seal & Cover	Seal & Cover
Change in Pavement Thickness, ft (in.)	+0.10 (1.0)	+0.25 (3.0)	+0.10 (1.0)	+0.35 (4.0)	+0.15 (2.0)

NOTE: All asphalt concrete mixtures are Grade D, except for the surface layer at Custer County Line West, which is Grade S. 1 ft = 0.3 m; 1 in. = 2.54 cm.
PMS – plant-mix surface
CTPB – cement-treated pulverized base
[a] Deep enough to penetrate past the existing overlay and into the original plant mix surface.
[b] Cement-stabilized the remaining plant-mix surface and part of the gravel base.
[c] Grade 4A aggregate.
[d] To remove the open-graded friction course.

West, which was MDT Grade S (Superpave). This Grade S lift extended across both the control item and the test item. All test and control sections were topped with a chip seal ("seal and cover") with a 0.95-cm (0.375-in.) maximum-size aggregate.

The control section at Bearmouth–Drummond did not involve an increase in pavement thickness above subgrade relative to the original pavement structure. The MDT design personnel did not believe an increase in structural capacity was necessary at this site. The final thickness of the control section at Rocky Canyon was the same as the original structure, but the structural capacity was increased through stabilization. The control sections at Lincoln Road–Sieben, Custer County Line West, and Tarkio East involved increases in thickness above a subgrade of 1.27 cm (0.5 in.), 12.7 cm (5 in.), and 5.1 cm (2 in.), respectively (see Table 8).

The structural capacities of the test sections at all sites were increased relative to the original pavement structures. Milling was deep enough to remove only the OGFC, so all overlay lift thicknesses were greater than the depth of removed material. Increases in total thickness above subgrade for the test sections ranged from 2.54 to 10.2 cm (1 to 4 in.), as indicated in Table 8.

PAVEMENT PERFORMANCE MONITORING

The test sections at each site have been monitored annually for changes in structural capacity, roughness, and visual distress. Structural capacity has been monitored with both a Road Rater and a Jils falling-weight deflectometer (FWD). (The switch to the FWD was part of a statewide shift to this device by the MDT pavement management system.) Roughness was monitored with a South Dakota profilometer. Distress monitoring has involved visual inspections of the road surfaces and, beginning in 1999, a Rainhart transverse profilograph.

Structural Capacity

The MDT transitioned from using a Road Rater to using a FWD in 1998. Structural evaluations performed in 1997 or earlier involved a Road Rater. Both Road Rater and FWD testing have been done every 127 cm (50 ft) within the test sections. Most tests are performed in the outer wheelpath of the traveling lane. Every fourth test, however, is performed in the outer wheelpath of the passing lane. Thus far, differentiating tests by lane for the purpose of analyzing results has not been deemed necessary.

During Road Rater and FWD testing, the applied force and pavement surface deflections were measured. Surface deflections were measured at the following horizontal offset distances from the load: 0 cm (0 in.), 20.3 cm (8 in.), 30.5 cm (12 in.), 45.7 cm (18 in.) (FWD only), 60.9 cm (24 in.), 91.4 cm (36 in.), and 121.9 cm (48 in.). Currently, the MDT retains only peak loads and peak deflections for analysis purposes. The peak deflections can be used to produce a deflection basin. The deflection basin, in combination with the known load and assumed layer thicknesses, can be used to estimate the elastic moduli of pavement layers.

Additional methods exist for using deflection basin data to characterize pavement materials. For example, an overall pavement response stiffness can be obtained by simply dividing the applied load by the deflection under the load (offset = 0 cm). The curvature of the deflection basin has also been used to deduce material characteristics. Although these simplistic data analysis methods provide less information than the results of backcalculation, they require no assumptions in terms of the number of layers or layer thicknesses. Therefore, the simplistic analysis methods have advantages when thicknesses are unknown or when the number of layers cannot be limited to a manageable amount. The simplistic analysis methods may have advantages when pavement structures that have experienced several cycles of rehabilitation are being analyzed.

Roughness and Rut Depth

Roughness monitoring was performed with a South Dakota profilometer, which is an inertial profiler. The South Dakota profilometer consists of a truck equipped with accelerometers and lasers. Pavement roughness measurements are obtained at speeds between 32 and 105 km/h (20 and 65 mph) (typically at 105 km/h). The accelerometers provide an inertial reference and the lasers are used to measure the distance between the inertial reference and the pavement surface.

Roughness has been reported as international roughness index (IRI) values, which have units of inches/mile (inches of vertical deviations per mile of road). As a pavement's roughness increases, its IRI increases. The MDT ranks the conditions of paved surfaces in terms of IRI as indicated in Table 9.

TABLE 9 MDT Ranking of Pavement Roughness

Condition of Paved Surface	International Roughness Index (inches/mile)
Excellent	< 16
Good	16 to 75
Fair	76 to 150
Poor	151 to 225
Very Poor	> 225

NOTE: 1 in. = 2.54 cm; 1 mi = 1.6 km.

The South Dakota profilometer uses two lasers for measuring pavement surface deviations in order to calculate IRI. These two lasers are attached so that they project into the two wheelpaths. The South Dakota profilometer has a third laser on the front bumper in order to permit calculations of rut depth. The third laser is attached so that it projects in the middle of the lane, centered between the two wheelpaths. As the vehicle travels along the road, 20 to 30 measurements are obtained by each laser per 0.3-m length of pavement. The differences between the lengths measured by the lasers are used to estimate an average rut depth:

$$\text{average rut depth} = \frac{(h_1 - h_2) + (h_3 - h_2)}{2}$$

where

h_1 and h_3 = distances to the pavement surface in the wheelpaths, and
h_2 = distance to the pavement surface at midlane.

To supplement the data collected by the South Dakota profilometer, a Rainhart transverse profilograph is being used to measure rut depths during the final two evaluation years (1999 and 2000). The Rainhart device consists of a solid metal beam upon which a drum with graph paper travels across a single lane of the highway. This produces a hard copy of the transverse profile in a 1:1 ratio in the vertical direction and a 10:1 ratio in the horizontal direction. At most test sites, 10 randomly chosen stations are used for profile measurements in the test sections and 10 are used in the control sections. At the Bearmouth–Drummond site, only 5 stations are used in each test and control section. The locations of the stations from the start of a test or control section are consistent at a single location. However, each site has its own random arrangement.

Measurement of rut depth from profilograph information is accomplished by first drawing a straight line at the highest points about each wheelpath. The maximum vertical depth from this line to the profile is then considered the rut depth. For analysis purposes, the greater of the two wheelpaths is used.

Visual Distress Survey

Visual examinations and the methods for recording distress generally followed the guidelines established by the

TABLE 10 Distress Types Included in Visual Examinations

Distress Type	Unit of Measure	Comments
Bleeding	Percent Length of Affected Area[a]	Discoloration is reported as low severity bleeding even though it may not have substantial effects on pavement performance.
Raveling	Percent Area	Raveling of the surface treatment is differentiated from raveling of the asphalt concrete.
Transverse Cracking	Number and Density (length / area)	Full-width cracks, which extend from shoulder stripe to shoulder stripe, are differentiated from partial-width cracks.
Longitudinal Cracking at Centerline	Percent Length	None.
Longitudinal Cracking in the Wheelpath	Percent Length	None.
Fatigue Cracking	Percent Area	None.
Potholes	Percent Area	None.
Patches	Percent Area	None.

NOTE: Each distress type can have three levels of severity: low-severity, moderate severity, and high severity. Judgment of severity is based on SHRP guidelines (*2*).

[a] Affected area could be one or both wheelpaths, centerline, or edge of lane; localized bleeding was not a problem for the pavements included in this study.

Strategic Highway Research Program (SHRP) (*2*). Some modifications were implemented to meet the specific needs of this study. For example, units of measure have been adjusted in some cases. The types of distress that were included in the examinations performed for this study are presented in Table 10.

PAVEMENT PERFORMANCE

Pavement evaluations at the test sites have been performed for only 1 or 2 years. None of the pavements has deteriorated so quickly that conclusions are warranted at this time. Therefore, this section of the report serves the purpose of presenting the types of information that have been collected and reduced. Current plans are to continue to collect the same information for the next few years.

Structural Capacity

Pavement layer moduli are backcalculated from Road Rater and FWD tests. Road Rater moduli are substantially different than FWD moduli. Relative to the FWD, the Road Rater appears to estimate lower moduli for surface course layers and appears to estimate higher moduli for base course and subgrade layers. This difference most likely is caused by the different types of loading—that is, vibratory versus impact. For this study, conclusions will be drawn from trends in structural capacity over several years of service. Therefore, to avoid additional data anomalies, future FWD tests are being done in a manner consistent with those performed to date.

Data obtained from all three FWD test loads [2495 kg (5,500 lb), 3629 kg (8,000 lb), and 4536 kg (10,000 lb)] were reduced. The MDT has not yet refined its method for selecting among or combining these data, so all will be retained and included in the analysis for this study.

In addition to reporting mean (average) statistics, this study will provide indications of variability. Variability will become important as differences between the performance of control and test sections have to be judged as significant or not. The variability of backcalculated moduli is commonly high, especially for surface course layers. The coefficients of variation (the standard deviation divided by the mean) of FWD surface moduli within experimental sections were 20 to 60 percent.

Backcalculated moduli will not be the only parameters used to monitor the structural condition of experimental sections. Two additional parameters, structural numbers and the pavement response stiffnesses, are being evaluated. Both of these parameters provide an indication of the structural condition of the overall pavement instead of differentiating between pavement layers. Compared with backcalculated moduli, they tend to be less variable within any particular experimental section. The structural numbers were calculated using layer thicknesses and layer moduli, in accordance with the 1993 AASHTO design guide (*3*). Pavement response stiffnesses were calculated by dividing peak FWD load by peak deflection at the point of impact.

Roughness and Rut Depth

The experimental pavement sections began their service with roughness values (IRI) of about 40 to 100, which correspond to MDT qualitative rankings of good to fair. The IRI values, soon after construction, were similar for the control and test sections at Rocky Canyon, Lincoln Road–Sieben, and Custer County Line West. At Bearmouth–Drummond and Tarkio East, the IRI values were higher for the test sections than for the control sections. The control sections involve more milling and thicker placements of new material, which should promote a smoother product relative to the thin milling and overlay used for test sections.

The experimental pavement sections began their service with average rut depths of 0.38 cm (0.15 in.) or less. No consistent differences were observed between ruts in the control and test sections. These rut depths were estimated with the South Dakota profilometer. Currently these measurements are being supplemented with the Rainhart transverse profilograph.

The 1999 Rainhart data were analyzed by treating each location as separate smaller experimental sites. With a 95 percent confidence interval, only the Custer County location is offering a difference in performance between the test and control sections. At this site the control section is offering better rutting resistance. Recall that the control sections had stripped material removed before they were overlaid.

Similar to the structural capacity data, variability information is being retained for roughness and rut depth. Variabilities for IRI and rut depth are reported as range and average standard deviation, respectively. The calculation of the IRI range for an experimental section is possible because the South Dakota profilometer presents an IRI for each wheelpath and for each 0.16-km (0.1-mi) length of pavement. The calculation of average standard deviation for rut depths is possible because the South Dakota profilometer presents an average and standard deviation for each 0.16-km length of pavement. These IRI and rut depth calculations are based on 20 to 30 measurements per linear foot of pavement.

Visual Distress Survey

Condition surveys have been performed each year of service for all the test sites. The Tarkio East site has been surveyed only once because of its later construction date. All the sites currently appear to be in good condition. No sites have evidence of fatigue cracking or pothole formation. All the sites have some level of bleeding or transverse cracking.

Bleeding is not necessarily a distress that will lead to performance problems. According to SHRP condition survey procedures (2), low-severity bleeding should be recorded if the surface is discolored by excess asphalt. This can occur without affecting skid resistance. If surface texture is affected, the bleeding is labeled as moderate. Most of the bleeding observed at the test sites was low severity. Tarkio East also had moderate-severity bleeding in the traveling lane wheelpaths.

All transverse cracks at the test sites are currently classified as low severity. According to SHRP condition survey procedures (2), low-severity transverse cracks are either unsealed with a mean width equal to 0.64 cm (0.25 in.) or they are sealed with sealant material in good condition. The Rocky Canyon and Lincoln Road–Sieben site's cracks have been sealed. The Bearmouth–Drummond site and the Lincoln Road–Sieben site have the highest densities of transverse cracks, whereas the Tarkio East site has not yet cracked. Control and test sections have experienced similar transverse cracking at most sites. At Rocky Canyon, however, the control section has cracked more than the test section.

Conclusions and Recommendations

Based on 1 to 2 years of monitoring the test sites, the following conclusions and recommendations appear to be warranted.

- Construction of the experimental sections was successful and will provide informative comparisons between two methods of rehabilitating stripped pavements.
- Because test sections involved a simple overlay, they resulted in an increase in pavement thickness at all test sites. Because control sections involved substantial milling before overlays were placed, final thickness could be controlled. Changes in structural thickness for control sections ranged from 0 to 12.7 cm (0 to 5 in.), depending on anticipated traffic conditions. Consequently, the sites provide for various scenarios under which the two methods of rehabilitation can be compared.
- Because of the different loading conditions provided by the Road Rater and the FWD, the use of results from both types of equipment does not appear to be reasonable for the purposes of this study. This study seeks trends in pavement condition over time, and the pavement layer moduli estimated by the two types of equipment are different. This finding reinforces the importance of maintaining a consistent method of using the FWD throughout the remainder of this project.
- Roughness values (IRI) soon after construction indicate that substantial milling and the placement of new material in multiple lifts provide for smoother pavements relative to simple single-lift overlays. Consequently, the control sections in this study generally began their lives with better smoothness than the test sections.
- The tendency for experimental sections to rut is important to this study. Although the South Dakota profilometer provided an indication of rutting, more detailed rut data were believed to be advantageous. Future site

evaluations are now supplemented with transverse profiles, which are obtained with a Rainhart profiler.

- The predominant visual distress at the test sites has been transverse cracking. The cracks have thus far remained in a low-severity condition. Substantial differences between control and test sections have not yet been observed at the test sites, perhaps with the exception of the control section at Rocky Canyon, which has cracked more than the test section.

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New York State Department of Transportation Safety Appurtenance Program
Alternative Application of Road Safety Audits

Jonathan S. Bray

The state of New York owns and maintains an enormous inventory of roadside appurtenances, including guide rail, signs, delineators, and drainage structures. Those roadside features exist for the convenience and safety of the motoring public. Historically, maintenance of roadside appurtenances has depended to a large degree on inclusion in the department's pavement resurfacing programs, particularly the previous resurfacing and preservation and ongoing resurfacing, restoration, and rehabilitation programs. Those resurfacing programs have been largely supplanted by the department's highly successful preventive maintenance paving (PMP) program. In fact, the share of miles of pavement being resurfaced each year under the PMP program has been increasing steadily since 1990 (from 44 to 72 percent of total miles resurfaced). Since the goal of the PMP program is limited largely to maintaining pavements, roadside appurtenances were not receiving the attention they required. The New York State Department of Transportation safety appurtenance program (an FHWA road safety audit pilot program) ensures that roadside appurtenances receive the attention they need under the PMP program in order to protect a sizable roadside investment and to ensure the safety of road users. The Offices of Engineering and Operations jointly proposed the plan that would involve maintaining existing safety features and adding appropriate, easily implementable, and low-cost safety treatments at PMP project locations either during construction or, more likely, after construction as part of a distinct but "linked" effort. Work not included in the PMP project could be undertaken by maintenance forces or under requirements type contracts (separate signing or guide rail contracts). The guiding principles behind the plan are that it not interfere with accomplishment of the primary goal of the PMP resurfacing program (pavement maintenance), that it not result in a reduction in the number of lane miles treated with PMP resurfacing, and that it not significantly delay or otherwise complicate the processing of PMP resurfacing projects. A regional road safety audit team (composed of staff from design, traffic, and maintenance areas) now reviews proposed PMP project locations for existing accident problems, based on an identified accident history or potential accident problems such as obvious, hazardous roadway features that can be readily identified during a field review, and recommends cost-effective improvements to address existing and potential accident problems. The design of the program, how it gained executive management approval, and some early program accomplishments are discussed. The initiative has proven successful not only because of its clearly defined benefits for two agency goals (highway maintenance and safety) but also because of the systematic process by which it was introduced to agency managers with sometimes conflicting needs and agendas.

The New York State Department of Transportation (NYSDOT) safety appurtenance program (SAFETAP) evolved in the early 1990s in response to a pavement maintenance initiative designed to ensure the maintenance of pavements at reduced cost. Called the

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preventive maintenance paving (PMP) program, this initiative called for a simple 3.8-cm (1.5-in.) overlay of pavements rated "fair" in order to avoid more extensive and expensive future treatments. The program proved effective in cost-effectively maintaining the state's pavements. However, whereas a process was designed to ensure that accidents did not increase as a result of the higher speeds associated with new roadway surfaces, opportunities to improve highway safety along the treated sections of roadway were not included in the program.

This decision—not to use this dedicated pavement maintenance program to address opportunities to improve highway safety—assumed added significance as more miles paved each year moved from the department's "standards-based" resurfacing, restoration, and rehabilitation (3R) program to the PMP resurfacing program. Historically, maintenance of roadside appurtenances (signs, guide rail, delineators, drainage structures) has depended to a large degree on the inclusion of those improvements in the department's pavement resurfacing programs, particularly the previous resurfacing and preservation and ongoing 3R programs. Between 1990 and 1997 the share of miles resurfaced under the PMP resurfacing program increased from 45 percent of total to 70 percent of total. This posed a serious problem not only from a highway safety perspective but also from a highway maintenance perspective. This finding was particularly significant in light of earlier findings of an evaluation study conducted by NYSDOT in the mid-1980s, which showed that simple resurfacing without roadside improvements contributed to an increased number of accidents during the 3 years after construction. On the other hand, accident rates tended to decline when roadside improvements were incorporated in the simple resurfacing projects. NYSDOT's evaluation results were confirmed in a more sophisticated statistical study of the same projects undertaken by Hauer et al. (*1*). Sponsors of SAFETAP viewed it as both an added opportunity to ensure against increased accidents in the short term after resurfacing as well as an opportunity to provide for long-term (permanent) reductions in the number of accidents.

Response of SAFETAP Sponsors

In response to these identified needs, the Offices of Engineering and Operations jointly proposed a plan that would incorporate safety considerations into the PMP program in a way that would not undermine the achievement of the program's primary pavement maintenance goals. This SAFETAP involved maintaining existing safety features and adding appropriate, easily implementable, and low-cost safety treatments at PMP project locations during construction, or after construction as part of a linked effort. Essential elements include the following:

- Examination of existing accident data as well as a site inspection to identify deficient roadside features and potential accident problems at each project site to determine specific safety related needs;
- Inspection by a team of experts (auditors) reflecting various functional areas within the agency (including traffic, maintenance, and design) with the appropriate expertise to assess existing and potential accident problems;
- Recommendations by the audit team of cost-effective solutions for those identified accident problems to agency leaders with responsibility for implementing proposed cost-effective accident countermeasures; and
- Reports each year to the Traffic Engineering and Highway Safety Division describing the disposition of recommendations and implemented actions.

The plan would effectively piggyback SAFETAP on NYSDOT's simple resurfacing PMP program. In doing so, it would carefully avoid interfering with accomplishments under the PMP program's pavement maintenance goals (including maximizing the numbers of miles resurfaced). Most recommended improvements would be accomplished before or after resurfacing. Only superelevation and shoulder improvements would be implemented during resurfacing. SAFETAP improvements would be undertaken by maintenance forces or with simple requirements contracts for signing, delineation, or guide rail. A fuller description of the program, as it was eventually approved, is contained in the department's engineering instruction 99-001, *1R Requirements—Federal-Aid Single Course Overlay Maintenance Paving Projects* (Appendix A).

Implementation Strategy

The SAFETAP program initiative anticipated and attempted to accommodate many of the competing concerns and needs that necessarily coexist in any large transportation agency. It accommodated maintenance staffing shortages by allowing and encouraging the use of special purpose contracts to accomplish the roadway improvements generated by the program. It accommodated the fact that infrastructure maintenance is perceived by many as the primary function of transportation agencies by minimizing the impact of the initiative on PMP resurfacing. At the same time, sponsors of the initiative recognized the existence of limited funds and that funding for a new initiative would mean that, unless new funds were found, some preexisting activities or projects would be sacrificed. Because a source of new funding was not available, or foreseen, sponsors of the SAFETAP initiative knew they had a difficult row to hoe.

It was decided to present the proposal to interested functional areas in the department (maintenance, design, and planning), gain their endorsement, and then present the proposal to executive management (main office commissioners and regional directors). This would allow sponsors of the program to address any additional concerns of the affected parties and to present a proposal to executive management that the agency could live with. FHWA provided additional, and very important, support for the process when it agreed to make simple resurfacing projects that were subjected to the SAFETAP program eligible for federal aid funding.

Agency Response

Response to the SAFETAP proposal was mixed. Most agreed that it is important to maintain safety appurtenances (signs, guide rail, median barriers, delineators, drainage facilities). But there were substantial differences on the cost of the program and the extent of coverage as well as on how the program was to be accomplished. Also, there was concern that expenditures on the maintenance of roadside features (as well as superelevation and shoulder improvements) would be subtracted from funds available for the department's paving programs, particularly the PMP program. This was particularly important, because the performance of many program areas and individual managers in the department is evaluated based largely on bridge and pavement (infrastructure) conditions. The proposal, therefore, was often viewed as directly challenging many competing, legitimate agency agendas. Department managers who viewed themselves as most directly affected by the proposal represented the maintenance, design, and planning functional areas.

Agency Approval

The SAFETAP concept was introduced to agency functional managers in spring 1996. After nearly 2 years of informational meetings and negotiated modifications, the proposal gained wide support in the department. The maintenance department eventually came to recognized that it (together with traffic) had most to gain from the program, because maintenance is, after all, the functional area responsible for roadside maintenance. This recognition overcame its concern about possible loss of PMP funds. The design department came to realize that applying judgment to addressing safety concerns on simple resurfacing projects is an adequate (and sometimes superior) substitute for applying set engineering standards (or for no consideration of safety at all). The planning department, which was primarily concerned about program funding issues, eventually accepted that the benefits of SAFETAP (to maintenance and safety goals) entitled it to a high-priority status in the agency.

Once general agreement was reached, sponsors of the proposal were able to gain executive management support for presenting the initiative to the departments' regional directors. NYSDOT's regional directors are the agency officials responsible for carrying out agency programs and goals. Fortunately, in large part because of the broad support for the proposal among functional managers in the main office, the regional directors accepted the initiative as an appropriate method for addressing both safety and infrastructure maintenance needs. Regional maintenance, in particular, viewed the program as an excellent process for identifying and addressing roadside maintenance needs. SAFETAP was formally accepted as a department program in September 1998.

Program Accomplishments

SAFETAP was approved for implementation in September 1998. Consistent with the program guidelines (contained in the engineering instruction), the department's 11 regional offices were asked to review all locations scheduled for resurfacing during the 1999 construction season and to report on planned and implemented actions affecting those locations by March 31, 1999. Table 1 indicates the types and numbers of improvements undertaken in three of the five regions (Binghamton, Watertown, and Hornell). SAFETAP in those regions alone generated 216 improvements including brush removal, shoulder work, sign installation and replacement, guide rail work, and drainage improvements. Because the program allows and encourages completion of roadside work before resurfacing, about half of the improvements (107) were completed at the end of March before the pavement was resurfaced.

This is now the second year of the program. As more data on program accomplishments are received, it is possible to ascertain certain patterns. Different types of improvements are emphasized in different regions. Audit teams in regions with strong maintenance forces tend to recommend improvements that are susceptible to implementation with maintenance forces. In regions with scarce or overstretched maintenance forces, audit teams tend to place more emphasis on improvements implementable under special purpose (guide rail or signing) contracts. Emphasis so far has been largely on the roadside needs of rural roads. In the future the more urban regions may extend their areas of concern to simple traffic management strategies, such as modifications to signal timing or phasing. These developments will be monitored with the intent of encouraging the regions to pursue a comprehensive and balanced approach to addressing safety appurtenance needs. However, a centrally important feature of SAFETAP is to allow those in the regions with responsibility for program implementation maximum flexibility in meeting their responsibilities. The program is therefore designed to balance the accomplishment of main office program goals with regional implementation goals.

TABLE 1 SAFETAP Accomplishments for Regions 6, 7, and 8, State Fiscal Year 1998

Activity	Treatment Sites	
	# of Sites	# Complete
Clear Brush Obstructing:		
Warning Signs	46	32
Traffic Control Signs	4	4
Sight Distances	37	28
Shoulder Work		
Back-Up Shoulders	5	2
Correct Shoulder Failure	4	3
Install Rumble Strips	3	0
Drainage Work		
Place Fill (Repair Holes etc.)	3	1
Repair Drop Inlets	4	1
Improve Drainage	0	0
Improve Ditch	1	0
Improve Surface Drainage	2	1
Add or Replace Signs		
Install Signs	4	2
Improve Signs	9	0
Adjust Signs	8	5
Replace Signs	22	13
Remove Signs	2	1
Install Chevrons	5	1
Install Speed Panels	1	0
Correct Speed Panels	1	0
Replace Delineators	4	2
Add Delineation	7	0
Replace Reference Markers	2	0
Guiderail Work		
Install Guiderail	5	1
Repair Guiderail	9	4
Adjust Guiderail Height	0	0
Tighten Guiderail Cable	5	4
Replace Guiderail Posts	3	1
Replace Guiderail	10	1
Extend Guiderail	4	0
Remove RR Rail Posts	1	0
Further Review	1	0
TOTAL ACTIONS	216	107

SAFETAP STRENGTHS

Following is a description of elements of the SAFETAP process that have contributed to its success:

• Team approach: SAFETAP relies on a team of auditors made up of representatives from the major functional areas of the department (traffic, design, and maintenance) with interest in highway safety and roadside feature maintenance issues. There are several advantages to this arrangement. First, the team approach benefits from the diverse knowledge and experience of the team members. Second, it encourages agency buy-in by involving diverse agency interests, representing SAFETAP broadly as a department-wide program instead of narrowly as a traffic or maintenance program. Third, the audit recommendations generated by the program have broad support from representatives from the major department functional interests. They are not simply offered by the functional area or areas with particular responsibilities (such as traffic with its concern for highway safety, or maintenance with its concern for maintaining roadside features). This arrangement greatly enhances prospects for receiving the support of agency decision makers for the implementation of recommended improvements, and it served to encourage maintenance buy-in for this overall approach to fulfilling their maintenance responsibilities.

• Audit scope: SAFETAP offers a balanced and straightforward flexible approach to addressing potential accident problems. It is not a standards-based program. It recognizes that, by themselves, standards are not sufficient to address project-related safety concerns. Nor does it confine itself to consideration of identified accident patterns. The central focus of SAFETAP is on applying audit team judgment and experience to resolving potential accident problems. It calls for a simple examination of accident histories and allows for the application of standards if, in the judgment of the audit team, the application of standards constitutes the appropriate, cost-effective solution to the accident problem (actual or potential). This balanced approach appealed to a variety of competing interests (and philosophies) in the agency and contributed significantly to program approval.

• Effect on agency resources: It was recognized at the beginning of the process that agency maintenance forces were substantially reduced over the preceding 10 to 15 years. Without outside assistance they would likely be overwhelmed with the prospect of considerable extra work. Therefore agency support was provided for special requirements type contracts to assist existing maintenance forces. This provided the safety valve they needed.

• Effect on other agency goals: Sponsors of the initiative stressed the aspects of the proposal that ensured that it not interfere with accomplishments under the department's pavement goal. More specifically, they emphasized that the guiding principles behind the plan were that it not interfere with the accomplishment of the goals of the PMP resurfacing program, that it not result in a reduction in the numbers of lane miles treated with PMP resurfacing, and that it not significantly delay or otherwise complicate the processing of PMP resurfacing projects. Based on these principles, resurfacing projects are not delayed, nor are miles of pavement treated each year reduced. Roadside safety improvements are, in most cases, undertaken before or after resurfacing. Exceptions to this general rule (superelevation or shoulder work) are accomplished during resurfacing without substantially modifying preexisting paving strategies. Were it not for this early, sustained emphasis on the accommodation of other competing agency agendas (in this case infrastructure goals) it is not likely that the SAFETAP initiative would have received the kind of broad-based agency support it needed to succeed.

FHWA Road Safety Audit Initiative

In the midst of this lengthy effort to gain department approval of the SAFETAP initiative, FHWA began an initiative to encourage the use of road safety audits in this country. Road safety audits, as presented under the federal initiative, are intended to supplement existing agency highway safety activities by directing a team of auditors to apply their knowledge and experience (engineering judgment) toward improving potentially hazardous highway features through better project design. FHWA has begun the process of clarifying the meaning of road safety audits, because the contours of the process (as they are careful to emphasize) have yet to be precisely defined in this country. According to FHWA's evolving definition of road safety audit, a team of "auditors" would examine project sites for the purpose of identifying and treating potential hazards. It calls for applying engineering judgment (not standards) toward the development of solutions to identified hazards and requires that a formal report of audit findings and recommendations be prepared and forwarded to agency decision makers for consideration.

There are a number of areas in which SAFETAP and conventional (or prevailing) views of road safety audits tend to differ. Prevailing views of road safety audits tend to emphasize their application to large-scale capital projects and downplay consideration of existing accident patterns (focusing instead on accident potential) and the application of standards. Those views also stress the importance of independence, failing to account for the importance of familiarity with agency culture (and agency buy-in) in ensuring implementation of audit recommendations. Those differences are discussed in detail elsewhere (2). That there are differences should not be a surprise, because the road safety audit concept originated in other countries facing different situations, and the approach is just getting under way here. It is important to note above all else, however, that, as a general approach to identifying and addressing highway safety needs, the road safety audit process, whatever its final form, offers great promise for contributing to the continuation of the dramatic decline in accident rates of the previous 35 years into the new century.

SAFETAP is a unique application of the road safety audit concept to simple resurfacing projects, which often are undertaken without consideration of highway safety needs. The process could fill a gap in many of this country's agencies, which address safety concerns for major capital projects through the application of carefully defined project development processes on the one hand but view simple resurfacing as limited to pavement maintenance (without consideration of highway safety) on the other. That FHWA recognizes the importance of filling that gap is demonstrated by its endorsement of SAFETAP as one of its road safety pilots. As indicated previously, FHWA's endorsement of the program and authorization of federal aid funding for simple resurfacing projects subjected to the program contributed substantially toward gaining department approval and support of the initiative.

Conclusion

PMP projects, together with resurfacing done under the capital (3R) paving program, address about 10 percent of the state's 25 750-km (16,000-mi) highway system each year. SAFETAP, by maintaining roadside assets, helps achieve maintenance goals by providing a systematic process for meeting the department's roadside maintenance responsibilities. By addressing roadside safety needs ensuring that highway safety considerations are included, SAFETAP also contributes toward achieving a major goal of NYSDOT's safety management system—the incorporation of transportation safety consideration in all agency activities. It contributes toward accomplishing two seemingly disparate agency goals: accident reductions and maintenance of roadside assets.

The success of the initiative is attributable not only to its clear benefits to highway safety and maintenance but also to the systematic process by which the concept was introduced to the department. Sponsors of the initiative recognized the importance of achieving consensus among affected agency program (functional) managers before they solicited support from regional implementation managers and, ultimately, executive management. That process required patience. It took more than 2 years of explanatory discussions and negotiations, as well as some compromise with diverse agency interests, before the program gained formal agency approval. The result has been institutionalization of a major department-wide program that, by systematically incorporating highway safety into hundreds of simple resurfacing projects, goes a long way toward continuing into the next century the sizable accident reductions that occurred in New York, and throughout the country, during the final decades of the 20th century.

Appendix A

New York State Department of Transportation Engineering Instruction: 1R Requirements: Federal-Aid Single Course Overlay Maintenance Paving Projects

This engineering instruction (EI) (see Figure A-1) does not supersede any older issuances.

Effective Date

This EI is effective immediately. To qualify for federal aid for single course overlays in state fiscal year 1999–2000, project site selection and review by the safety audit team, as described, should begin immediately. Selection of the appropriate safety work and completion of SAFETAP Report Form A, as described, should be completed by March 31, 1999. 1R paving projects and safety work identified after submission of the SAFETAP reporting forms on March 31 may be progressed within the same state fiscal year by submitting an amended SAFETAP Report Form A.

Purpose

The purpose of this EI is to identify the 1R requirements for federal aid single-course overlays and to transmit the following supporting information:

- Requirements and guidance for safety work;
- SAFETAP report form requirements;
- Sample SAFETAP Report Form A;
- Sample SAFETAP Report Form B;
- Safety screening, dated January 27, 1994; and

New York State Department of Transportation
ENGINEERING INSTRUCTION

EI
99-001

Title: **1R REQUIREMENTS — FEDERAL-AID SINGLE COURSE OVERLAY MAINTENANCE PAVING PROJECTS**

Distribution:
☐ Manufacturers (18)
☒ Main Office (30)
☐ Local Govt. (31)
☒ Regions/Agencies (32)
☐ Surveyors (33)
☐ Consultants (34)
☐ Contractors (39)
☐ ______________ ( )

Approved:

Robert A. Dennison
Deputy Chief Engineer (Design) 1/20/99 Date

FIGURE A-1 NYSDOT engineering instruction letterhead for distribution of 1R requirements.

• Pavement preventive maintenance projects second working draft, dated February 12, 1993.

1.0 Background and Applicability

P. T. Well's and C. A. Thomas's September 8, 1998, memo issued the department's guidelines for SAFETAP. SAFETAP is an initiative designed to ensure that safety considerations are incorporated into the department's maintenance paving projects. SAFETAP requires a project review of maintenance paving sites by a team of qualified department staff for the purpose of deciding on safety work to be implemented before, at the time of, or soon after, construction.

FHWA has approved single course overlay PMP projects and vendor in-place paving (VPP) projects for federal aid, provided they meet the requirements of this EI. For simplicity, this EI is referred to as the 1R requirements. These requirements, in effect, take the place of SAFETAP guidelines in order to make PMP and VPP projects eligible for federal aid.

The SAFETAP guidelines remain in effect for 100 percent state-funded maintenance paving projects, including PMP and VPP projects. However, all PMP and VPP projects meeting the 1R requirements in this EI are eligible for 100 percent state as well as federal funding. This allows greater flexibility in the fund source.

1.1 Responsibility

• Responsibility for implementing this program is shared among the design, traffic, maintenance, planning, and other groups within each region, as determined by the regional director.

• Decisions about disposition of the safety audit team recommendations for work that is practical and necessary to address existing or potential safety problems, as discussed in Sections 2.1 and 2.3 of this EI, reside with the regional director. [Note that safety work needed to avoid degrading safety that will not be accomplished shall be treated as a nonstandard feature in accordance with the *Highway Design Manual* (HDM) (Section 2.8) and the TEA-21 matrix in the *Design Procedure Manual*.]

• The responsibility for programming and scheduling the implementation of safety work, as discussed in Section 2.4 of this EI, resides with the regional director.

• Program reporting, as defined in Section 2.5 of this EI, is the responsibility of the regional traffic group, unless the regional director decides to assign it to another regional group.

2.0 Requirements

The 1R requirements are based on SAFETAP guidelines and the attached pavement preventive maintenance projects second working draft and safety screening. As the SAFETAP guidelines apply only to 100 percent state-funded maintenance paving projects, this EI takes the place of the SAFETAP guidelines for federal aid single-course overlays. This EI also modifies or clarifies the attached documents by adding the following 12 requirements.

• The project must be competitively let and the work by state forces cannot be an integral part of the contract for the paving work (e.g., state forces doing the maintenance and protection of traffic work for VPP).

• VPP projects let by the Office of General Services must meet all federal aid contracting requirements. The regional maintenance group or the main office maintenance division should be contacted to determine the general requirements for VPP projects.

• Work done by state forces is not eligible for federal aid.

• Overlays are limited to a single course with a maximum thickness of 50 mm. Multiple course federal aid resurfacing projects shall be progressed as 3R projects in accordance with the *Design Procedure Manual* and HDM (Chapter 7).

• The existing pavement must have a pavement surface condition rating of 6 or greater. Exceptions must follow the pavement treatment selection in EI 92-015 "Project Level Pavement Selection Process" and be approved on a case-by-case basis by the regional director.

• Truing and leveling is to be used at spot locations to remove irregularities in the old pavement, fill and patch holes, correct variations in banked pavement, establish pavement crowns, and terminate the overlay as noted in the HDM (Section 3.3.1). Truing and leveling is not to be used over substantial lengths of the project to effectively increase the overall maximum overlay thickness or add a second pavement course. Wheel ruts are to be filled with a shim course or top course material. The intent is to fill ruts to improve surface drainage and allow adequate compaction of the overlay without adding a second hot-mix asphalt course.

• Milling of 50 mm or less may be performed for the traveled way or traveled way and full depth shoulders to maintain the existing surface elevation. Reasons for milling include maintaining vertical clearances, maintaining proper barrier heights, maintaining curb height for drainage, and replacing a poor top course on a sound pavement structure.

• The overlay must extend the full width of the paved roadway (travel lanes and paved shoulders) unless milling is performed as noted above and the paved shoulders, if any, are in satisfactory condition.

• The safety audit team must inspect each site as outlined in Sections 2.2 and 2.3 of this EI.

• The nonpavement work must be performed in accordance with Sections 2.1 and 2.4 of this EI.

- A report is prepared in accordance with Section 2.5 of this EI.
- The contract is not restricted to the 10 contract items as stated in Attachment 6 (not provided here).

2.1 Safety Treatment Criteria

Safety work that meets either of the following criteria is to be implemented under the 1R requirements:

- Safety treatments are necessary to avoid degrading safety, or
- Safety treatments are practical and necessary to address existing or potential safety problems.

The safety work is to be identified by completing a safety audit, as described below.

2.2 Site Selection

During the early summer months, the regional maintenance group together with the regional planning and program manager and the regional pavement manager decide on locations that are to be progressed under the 1R requirements in order to qualify for federal aid.

2.3 Safety Audit Team

Before or during site selection, the regional director should assign one or more experts from each of the regional traffic, design, and maintenance groups, and any other regional groups he or she determines to be appropriate, to become part of a safety audit team. The safety audit team should review the selected sites soon after project selection to ensure that adequate plans can be made for any superelevation work to be included in the project.

The team will perform a simple analysis of site-related computerized accident data, examine the sites selected, and make recommendations for safety work. Safety work that meets the criteria in Section 2.1 should be recommended by the safety audit team and should be decided/scoped at the time of the on-site inspection. Requirements and guidance for conducting a safety audit and preparing the subsequent safety work are included in Figure A-2.

2.4 Type and Timing of Safety Work

This section includes a list of typical safety work with the timing of when the work should be accomplished. Ideally, the safety work should be done before or immediately after the paving work in order to minimize the public's exposure to existing or potential safety problems. However, scheduling the work requires consideration of the following:

- The need to mitigate accident problems;
- The potential for future accidents;
- The extent, complexity, and staging of the work involved;
- The impacts of winter shutdowns; and
- Contractor or state force availability.

Therefore, while the following list of safety work contains general time frames, the most critical safety needs should be addressed earlier. Additionally, safety work, such as brush removal, clearing, and grubbing, may be completed before the paving operation, as appropriate.

Note that implementation of the safety work items identified by the safety audit team and approved by the regional director is to be programmed or scheduled and reported on SAFETAP Reporting Form A as required by Section 2.5 of this EI. The work may be accomplished as part of the paving contract, as part of separate contract(s), by state maintenance forces, or by others under a highway work permit.

To be done before the paving contract, as required:

- Replace missing regulatory or warning signs as noted by the safety audit team.

To be done during the paving contract, as required:

- Superelevation.
- Shoulders.
- Interim treatment for edge of pavement drop-offs shall be provided in accordance with Section 619-3.01 G.3 of NYSDOT "Standard Specifications" and shall continue until the edge drop-offs are corrected.

To be done during or as soon as possible after completion of the paving contract, as appropriate (the safety work normally should be completed within 2 months of the paving work, unless otherwise specified; as an exception, safety work needed to supplement paving work completed near the end of the construction season may be deferred to the first couple of months in the following construction season if its completion within 2 months is impractical; pavement markings, regulatory signs, warning signs, critical guide rail, and other work to mitigate an accident problem are not included in this exception):

- Pavement markings (refer to specifications and current EIs for timing);
- Rumble strips;
- Back-up shoulders to eliminate edge drop-offs;
- Additional/updated regulatory, advisory, and warning signs not addressed (generally within 2 months);
- Brush removal, clearing, and grubbing;
- Fixed objects: remove, modify, relocate, delineate, or protect by guide rail;
- Guide rail:
  - Reset guide rail that is or will be at the improper height,

Project Location & Limits	Route = From = To = Municipalities =	
Safety Audit Team Members & Regional Program Areas	Design = Traffic = Maintenance =	
Date		

–	Element	Guidance	Comments
	Signing	• Signs should be installed as needed in accordance with the NYS MUTCD. • Immediately notify the Resident Engineer of any missing regulatory or warning signs.	
	Superelevation	Consult Figure 231-1 of the NYS MUTCD. Identify any current conditions which meet the criteria in Section 2.1 (i.e., curves where it is determined that existing operating speeds are now causing, or may in the future cause, vehicles to travel off the roadway or cross the centerline.) Sharp horizontal curves may be ball banked to help determine the need for additional superelevation. Existing superelevation should not be reduced unless excessive (>8%) and causing a safety problem. Where the superelevation will not be improved to the minimum required for the speed limit, install advisory speed signs and consider additional treatments (e.g., chevrons, roadside clearing, etc.)	
	Shoulder Resurfacing	Consider paving unpaved, stabilized shoulders based on the need to reinforce the edge of the traveled way, accommodate bicyclists or treat safety considerations.	
	Rumble Strips	On rural, high speed facilities (55 mph & 65 mph) consider in accordance with HDM §3.2.5.4.	
	Pavement Markings	Pavement markings should be installed in accordance with the NYS MUTCD. The adequacy of existing passing zones should be evaluated. Current EI's and specifications must be followed.	

FIGURE A-2 Requirements and guidance for safety work. (NYS MUTCD = New York State Manual on Uniform Traffic Control Devices, SSD = stopping sight distance, SDCD = Structures Design and Construction Division, DQAB = Design Quality Assurance Bureau). (*continued on next page*)

	Element	Guidance	Comments
	Sight Distance	Trim vegetation to improve substandard intersection sight distance, and horizontal and vertical stopping sight distance. • Intersection Sight Distance - HDM § 5.10.5.1 A • Passing Sight Distance - HDM § 5.8.2.2 • Horizontal & Sag Vertical SSD - HDM Chapter 2 and HDM § 5.8.2.1	
	Fixed Objects	Based on the criteria in Section 2.1 of this EI, remove, modify, relocate, delineate, or protect by guide rail any fixed objects that require remediation due to existing or potential safety implications (e.g., tree removal on the outside of a curve or installation of traversable driveway culvert end sections on the outside of a curve). The Safety Audit Team should determine the timing of the work based on the work involved, accident data and accident potential. For guidance on identifying fixed objects, refer to HDM §10.3.1.2 B.	
	Guide Rail	The following should be used to evaluate the need for guide rail and other roadside work. • HDM Section §10.2.2.1 - point of need • HDM Table 10-7 - acceptable guide rail height • HDM Section §10.3.1.2 B - guidance on determining severely deteriorated guide rail and non-functional guide rail • HDM Section §10.2.2.3 and Table 10-3 - barrier deflection distance • HDM Section §10.2.2 - design of new guide rail	
	Bridge Rail Transitions	The Regional Structures Group, Regional Design Group, SDCD and DQAB should be contacted, as necessary, to help identify substandard connections to bridge rail and for the recommended treatment.	
	Delineation	Delineation should be installed in accordance with the NYS MUTCD	
	Other		

FIGURE A-2 (*continued*) Requirements and guidance for safety work.

– Replace severely deteriorated and nonfunctional guide rail,

– Replace severely substandard guide rail and connections to bridge rail (e.g., concrete post/cable or railroad rail post/cable),

– Install guide rail if missing or not extending to the point of need if a serious hazard such as a cliff, deep body of water, or liquid fuel tank is exposed and there is a reasonable expectation that vehicles will reach the hazard,

– Restore guide rail deflection distance through clearing and grubbing; and

• Delineation.

To be done in a timely manner after the completion of paving (within 18 months of the paving work)

• Guide rail not addressed under the "as soon as possible" work,

• Replacement of missing or damaged reference markers,

• Fixed objects that cannot be practically addressed as soon as possible,

• Installation of guide signs/route markers if needed, and

• Any other features of concern that are judged to meet the criteria outlined in Section 2.1 of this EI.

2.5 SAFETAP Reporting Requirements

In accordance with the need to monitor the effectiveness of the 1R requirements, SAFETAP Reporting Forms A and B, as detailed below and presented in Figures A-3 and A-4, must be completed each year. The completed SAFETAP reporting forms are to be sent to the safety program management bureau by the end of the state fiscal year (March 31) for the scheduled and completed maintenance resurfacing projects. (Note that yearly submission of the SAFETAP forms should include the 100 percent state-funded projects, as required by the *Safety Appurtenance Program Guidelines*.)

1R paving projects or safety work identified after submission of the SAFETAP reporting forms on March 31 may be progressed within the same state fiscal year by submitting an amended SAFETAP Report Form A.

SAFETAP Reporting Form A (See Figure A-3)

• A listing of all sites selected for maintenance paving. This includes the following:

– Preventive maintenance paving projects using the 1R requirements (federal aid),

– VPP using the 1R requirements (federal aid),

– VPP with 100 percent state funds,

State Fiscal Year _____ Prior to Maintenance Paving Work

MAINTENANCE PAVING PROJECTS TO BE IMPLEMENTED IN NEXT SFY

1R Site		Fund Source	Team Recommendation	Regional Approval or Disapproval	Reason(s) if Rejected	Scheduled Completion Date
Beg. RM	End. RM					
1. 24 0303 1101	1141	Federal				April, 1999
1122	1122		Superelevation	Disapprove	1. Insufficient ROW 2. Curve sign and delineation should address the problem	N/A
1121	1121		Curve Warning Sign	Approve		May, 1999
1121	1123		Post Mounted Delineators	Approve		May, 1999
1134	1134		Guide Rail Replacement	Approve		June, 1999
2. 27 0304 2104	2139	State				July, 1999
2113	2115		Chevrons	Approve		August, 1999
2122	2124		Guide Rail Removal	Approve		September, 1999
2133	2133		Transition to Bridge Rail	Approve		September, 1999
3. 24 0303 1155	1190	Federal	No Recommendations	N/A		October, 1999

FIGURE A-3 Sample SAFETAP Reporting Form A: recommendations (SFY = state fiscal year, RM = road maintenance, ROW = right-of-way, N/A = not applicable).

1R Site		Fund Source	Resurfacing Complete	Improvements	Completion Date Month/Year
Beg. RM	End. RM				
1. 25 0303 1101	1161	State	May, 1999		
1137	1138			Post Mounted Delineation	June, 1999
1148	1149			Post Mounted Delineation	June, 1999
2. 25A 0302 1068	1087	Federal	June, 1999		
1077	1078			Superelevation	June, 1999
3. 27 0304 1139	1146	State	July, 1999		
1141	1143			Guide Rail Replacement	October, 1999
4. 101 0301 1004	1012	Federal	May, 1999		
1006	1008			Chevrons	August, 1999
1010	1011			Chevrons	August, 1999

FIGURE A-4 Sample SAFETAP Reporting Form B: completed safety improvements (RM = road maintenance).

– Resurfacing by state forces with 100 percent state funds, and

– Simplified maintenance contracts with 100 percent state funds using the pavement preventive maintenance projects second working draft.

This listing should include the beginning and ending reference marker for each site.

• The fund source (federal aid or 100 percent state funded).

• A brief description of the safety work recommended by the safety audit team for each site. Safety work needed to avoid degrading safety shall be explicitly identified as such.

• An accounting of the disposition of those recommendations. If any recommendations for safety work practical and necessary to address existing or potential safety problems are not approved for implementation, an explanation should be given for that decision. (Note: Safety work needed to avoid degrading safety shall be treated as a nonstandard feature in accordance with the HDM Section 2.8 and the TEA-21 matrix in the *Design Procedure Manual* if not addressed.)

• The scheduled timing of when the paving and related safety work will be (or was) accomplished.

SAFETAP Reporting Form B (See Figure A-4)

• A listing of all sites paved—this listing should include the beginning and ending reference marker for each site;

• The fund source used for the paving work;

• The year and month when the paving was done and the year and month when the safety recommendations were implemented; and

• The improvements made and the date when they were completed or scheduled to be completed, in accordance with Section 2.4 of this EI.

2.6 Records Retention

As a minimum, the project files relating to the safety audit and the safety work performed should be retained by the region until the next time the project limits are resurfaced or pending litigation is resolved.

Contacts

Design-related questions about this EI should be directed to your regional quality control engineer. Further questions may be directed to the main office safety program management bureau or your regional liaison engineer in the design quality assurance bureau.

References

1. Hauer, E., D. Terry, and M. S. Griffith. Effect of Resurfacing on Safety of Two-Lane Rural Roads in New York State. In *Transportation Research Record 1467*, TRB, National Research Council, Washington, D.C., 1994, pp. 30–37.
2. Bray, J. S. Safety Appurtenance Program, NYSDOT's Road Safety Audit Pilot. Presented at 69th Annual Meeting of the Institute of Transportation Engineers, Las Vegas, Nev., Aug. 1999.

Part 2

MAINTENANCE SAFETY AND WINTER OPERATIONS

Teamwork in Winter Maintenance
First-Hand Experiences

Airi Hellman and Eeva Nikulainen

When the Finnish National Road Administration (Finnra) was internally divided into administrative and production branches in 1998, it brought great changes on both organizational and operational levels. This internal division clarifies the roles and responsibilities of the branches, intensifies the efficiency of road management, and helps prepare the agency for open competition in public road management scheduled to be implemented starting in January 2001. The creation of winter maintenance teams in the same year was intended to both increase efficiency and decrease the costs of maintenance work. It entailed quite a radical change from the traditional work style (management by supervisors) to self-ruling worker teams. The teams were given contracts for the winter maintenance work, and they decided and planned how best to complete the work to fulfill the quality requirements set by the client—in this case, Finnra.

Since early 1998, the Finnish National Road Administration (Finnra) has operated as an agency divided into two units: Road Administration, a public authority that commissions road maintenance services ("client"), and Production, which provides road management products and services ("contractor"). The new organizational chart is presented in Figure 1. This internal division clarifies the roles and responsibilities of the branches, increases the efficiency of road management services, and helps prepare the agency for open competition in public road management, scheduled to be implemented starting in January 2001. Work will remain open to competition through 2004.

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Background

Finnra Production is divided into four operational areas: contracting, consulting, road ferry services, and export services. These areas are made up of contracting units that are awarded contracts for road management work and service in their respective areas. Maintenance contract area bases serve as actual home bases for both personnel and equipment.

Finnra Production operations are based on process and team organization. At the moment, the four kinds of teams are work, support, contract, and leadership. In this paper, I concentrate on the work teams only.

Work teams for winter maintenance were first introduced from October 1998 to April 1999. Although there was no precedent of such work teams in winter maintenance, a team of two drivers had been given their own snow plowing route for the entire winter season in central Finland. These people had been responsible for clearing snow and deicing certain road sections, and they were quite independent in their work.

For the work teams to be operationally possible, certain conditions are necessary. The workers must be highly qualified professionals. Although one of the teamwork concepts is to develop the skills of the team as a whole as well as those of its individual members, the basic profes-

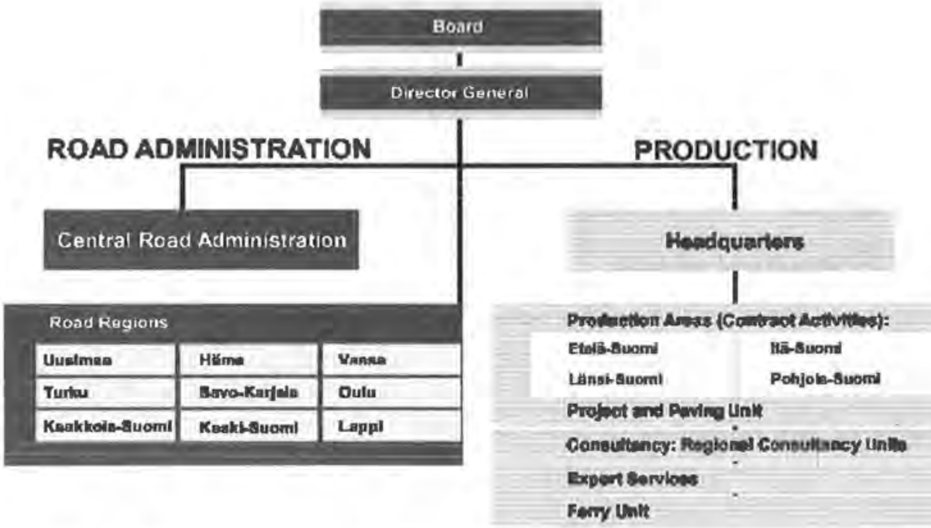

FIGURE 1 Organization chart of the Finnish National Road Administration.

sional competence has to exist. The state-of-the-art vehicle fleet and equipment must be in top condition, and maintenance must be well organized.

Today's drivers are workers skilled in many areas. Team members must have good local knowledge of both geography and traffic. It also helps if they have adequate working experience in their specific maintenance area and familiarity with previous work planning, routing, and output-based costs. It takes 2 to 3 years to train a new recruit with a driver's license to be familiar with all the necessary equipment and working methods in both summer and winter maintenance. Figure 2 is a photo of the interior of a modern SISU truck cab with all the different control devices. The latest addition is the computer, in which the driver inputs information about the work assignment. The data are transferred to the central database for use in calculating wages and maintenance costs and for quality reporting.

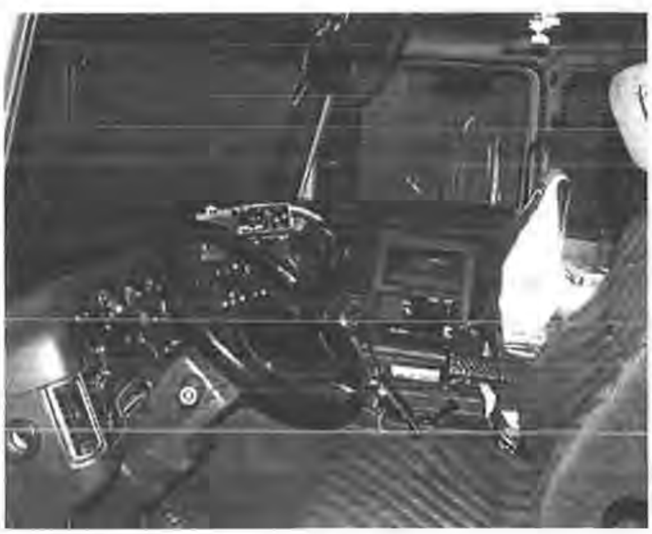

FIGURE 2 Inside a SISU truck cab.

Without the introduction of the road weather information system with road weather stations and service centers, self-ruling winter maintenance teams would not be possible. Whereas previously the order for starting maintenance operations was given by a supervisor on the basis of his assessment of the weather situation and road conditions, the alarm is now raised by the road weather centers (RWCs), which contact the team leader on duty. The team leader then acts on the information and suggestions received. The operational principle of the road weather information system is presented in Figure 3.

The ultimate purpose of Finnra Production in creating self-ruling worker teams for winter maintenance is to increase efficiency, cut costs, and encourage worker participation in decision making to make work more interesting and meaningful for the workers. In light of the future situation (open competition in road management services), Production needs to streamline its operations. Ultimately, this means that more work is done in less time and by fewer workers than before.

SELF-RULING WORKER TEAMS

In 1998, the decision was made to carry out all winter maintenance work by self-ruling worker teams in all maintenance contract areas. Three different contract models were drawn for the teams to choose from. The differences in these models were based on different ways of calculating remuneration for the contracted work. The basic idea in all of the contract models was to provide the workers with total basic wages, with no paid overtime. Teams chose two of the contract types, and Finnra's wish to have only

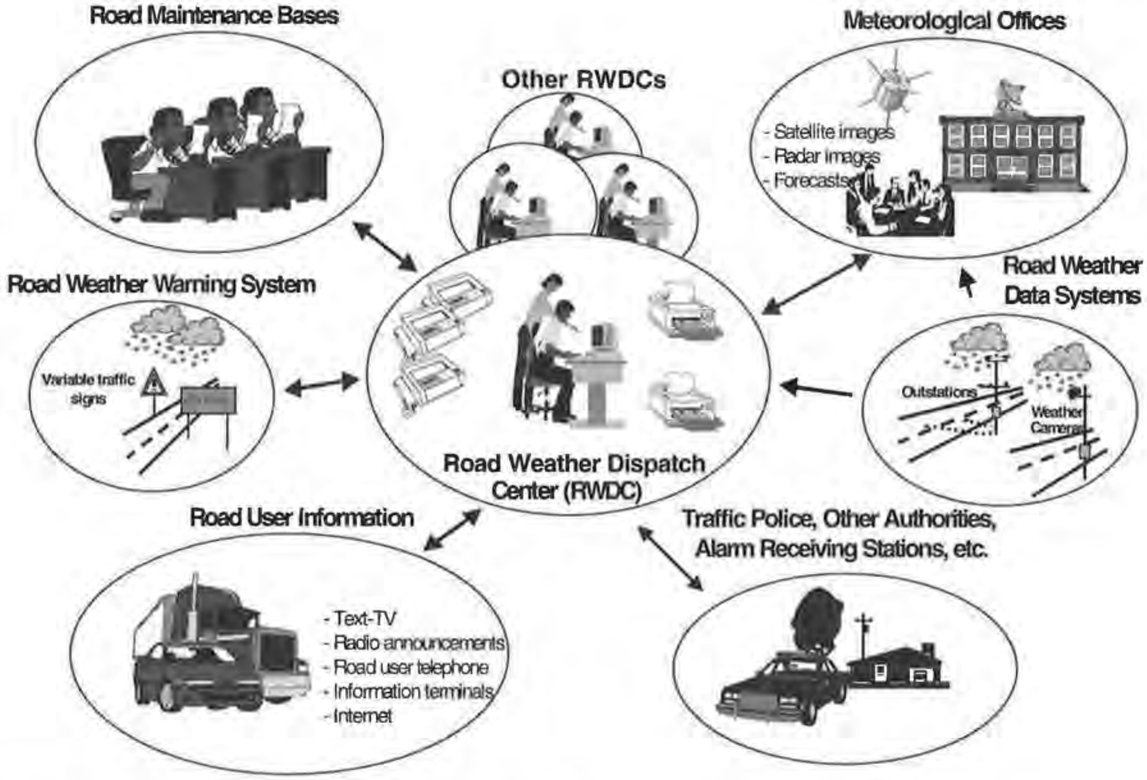

FIGURE 3 Operational principle of the road weather information system.

one kind of contract for all teams did not materialize. The contracts describe the work to be carried out by the teams in their specific maintenance areas. Quality for maintenance work is set by Finnra in the classification of roads and maintenance.

The teams organize their work independently, creating on- and off-duty as well as holiday schedules by themselves. Each team selects a new team leader each week, and the team leader position is rotated among all team members. All members are collectively responsible for the work and its quality. Instead of a maintenance supervisor giving them orders (what to do and when to do it), the teams make decisions themselves based on the information they receive from the RWCs. The RWC duty officer contacts the team leader, who then conveys the alarm to all team members.

The teams also have the right to sell maintenance services outside of Finnra. They can provide services such as sanding, deicing, and plowing to the private sector at agreed-upon prices. However, as yet, the team members have not actively marketed their services.

First-Hand Experience

When the self-ruling worker teams were first introduced, from October 1998 to April 1999, there was quite a lot of opposition. Drivers were suspicious of the new system and its merits. It was very difficult for the drivers to accept the radical change in the organization and the management of their work. The fact that the drivers' average age and working years were relatively high did not make matters any easier. In the end, most of the drivers signed the team contract and participated in the self-ruling worker teams. For instance, in the Helsinki Metropolitan Maintenance Contract Area only 2 of 67 drivers decided not to sign the contract.

The Helsinki Metropolitan Maintenance Contract Area has six self-ruling worker teams for winter maintenance. The number of drivers on each team varies from 6 to 18 depending on the amount of contracted work. Every team chooses its own team leader, and the role of the team leader is rotated among all team members. The system also provides for one "head" team leader for every three teams. The drivers have found the team leader duties very difficult and tiring. Their previous roles as professional drivers—doing only what was assigned to them—have suddenly changed to supervisory responsibilities for personnel, equipment, and work. As a backup, a road engineer is always on duty for technical problems, but the team leader has to take the initiative and give orders to the drivers. The organization of the Helsinki Metropolitan Maintenance Contract Area teams is presented in Figure 4.

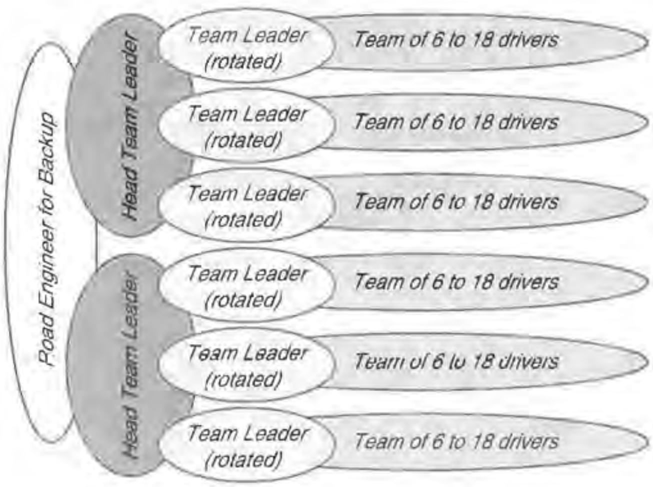

FIGURE 4 Organization of the Helsinki Metropolitan Maintenance Contract Area teams.

During the first contract period, winter weather was harsher than usual. Compared with data from the previous year, the number of alarms increased by 50—from 120 in 1997 to 170 during the contract period. The amounts of sand and salt used prove the same point: 13,000 tons of salt (NaCl) in 1998–1999 compared with 10,500 tons in 1997, and 12,000 tons of sand in 1998–1999 compared with 10,000 tons in 1997. As many as three alarms could sound within 24 h, with no regard as to whether it was a weekend or a holiday. Normally, half of the team worked during the day, and the rest of the team was at home with standby duties. This situation made it rather difficult to plan one's leisure time, because when the alarm came, the drivers had to report to work with about one hour's notice. In addition, drivers on standby were not permitted to drink alcohol.

One example of this difficulty is illustrated in how the teams worked through Christmas 1998. The temperature on December 24 (Christmas Eve) dropped to 0°C, and it started snowing. The teams—12 trucks and 1 road scraper—started to spread salt and plow at 3 p.m. and continued until 9:30 p.m. It should be mentioned here that in Finland, our main Christmas celebration takes place on Christmas Eve, in the evening. The next alarm came on December 25 (Christmas Day) at 3 a.m.; salt spreading and plowing continued until 1:15 p.m. The work had to be resumed the same day at 8:25 p.m. and was not finished until the next morning (December 26) at 5 a.m. Work resumed December 26 at 4 p.m. and finished at midnight. After this experience, the drivers were very unhappy because they had had no time to celebrate Christmas with their families.

The question of overtime has become problematic. According to the Finnish labor legislation, the amount of annual overtime is restricted to 250 h. An additional 80 h is possible with the consent of the worker and the permission of the shop steward. The teams were not used to taking these regulations into consideration, but now it has been brought to their attention through training, and they follow the regulations.

Some of the winter maintenance work was outsourced to the private sector. Cooperation between Finnra teams and the private contractors did not always come off without problems. In some cases, the quality of work by the private contractors was not high enough, and Finnra teams had to do extra work. Understandably, such occurrences did not promote mutual cooperation.

As to the savings in winter maintenance provided by this new system, no official report is available as yet. However, some personal observations have been made.

The cost of winter maintenance has not decreased; possibly it has increased. Teamwork seems to have increased the amount of overtime and work on Sundays. Although the team members receive no extra pay for overtime, work on Sundays and holidays (such as Christmas) is compensated. All in all, the number of hours worked per driver has increased.

The number of operative personnel has decreased, and the new role of the supervisors has decreased their overall numbers. The number of operative personnel used to be twice the number of the entire vehicle fleet, including vans and light trucks. Now, the figures are 1.3 to 2 times the number of the main vehicle fleet (that is, heavy trucks and graders). Nevertheless, the use rate of the equipment has increased. The lengths of the plowing routes have increased, which can be attributed to increased efficiency.

CONCLUSIONS

The requirements for a successful team concept are shown in Figure 5.

Building a good self-ruling team with cooperative working ability and tradition takes several years. This process cannot be accelerated, but it can be helped by professional facilitators through training. The ideal situation would be that a team could choose its own members, but in the case of Finnra Production's self-ruling worker teams, this was not possible. The teams are com-

FIGURE 5 Requirements for a successful team concept.

posed of drivers that the maintenance contract areas already employ, and because Production is downsizing personnel, new recruits are not possible. In the future, drivers will be members in more than one team, as many Production employees already are.

In addition to training the entire team in cooperative working methods, ideally, each team has at least one induction trainer. In other words, one of the team members has been trained to train his colleagues in new working methods, use of equipment, and so on. There is a great need to maintain and continuously update the teams' professional competence. Finnra has a long tradition in training its own personnel to become trainers in their own expertise, whatever that may be. These trainers are chosen on the basis of their professional competence, willingness to train others, and suitability to work as trainers.

Sharing information among the team members needs to be improved. Some drivers have complained that information does not reach all members of the team equally. It has been suggested that to remedy the situation, team meetings be organized regularly—on a weekly or twice-monthly basis.

Meetings also would help to build motivation among team members. The fact that everyone receives the same wages regardless of their input may weaken an individual's motivation, especially if the division of work is considered to be unfair. There always are some people who are naturally very productive and others who need more time to accomplish assigned tasks. Self-empowerment that comes from bringing decision making closer to the workers makes the work more interesting and consequently helps to increase motivation. Being able to take one's own initiative in carrying out one's work and being commended for it is also motivating. Better job satisfaction works toward greater commitment, which in turn leads to greater efficiency—and that is the objective of self-ruling worker teams.

Centrally Organized Temporary Traffic Control Team

Piloting an Independent Profit Center

Jukka-Pekka Lepistö and Päivi Martikainen

At the end of 1998, the South Finland Production Area of the Finnish National Road Administration (Finnra) decided to create and pilot test a new service system to take care of temporary traffic control during road work. The new Finnra team offers all-inclusive temporary traffic control services to anyone who needs them—inside or outside Finnra. The team applies for working permits, takes care of traffic arrangement, and develops and tests new traffic control equipment under local conditions. The team, a pioneer in work-zone safety, works toward four goals: maximum safety to the road users, maximum safety to workers, minimum delay on site, and optimal economy for the client. The project started at the end of 1998; the pilot "traffic control team" idea was tested in 1999; and the team officially started work at the beginning of 2000.

Since the beginning of 1998, the Finnish National Road Administration (Finnra) has operated as an agency divided into two units: Road Administration, a public authority that commissions road maintenance services ("client"), and Production, a unit that specializes in road management products and services ("contractor"). Figure 1 is the new organizational chart. This internal division clarifies the roles and responsibilities of the branches, intensifies the efficiency of road management, and helps prepare the agency for open competition in public road management scheduled to be implemented in January 2001.

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Background

Specific requirements for temporary traffic control are written into Finnish law. In addition, Finnra set guidelines for temporary traffic control in the early 1990s (Traffic on the Construction Site [TIEL 2272000] and Traffic Arrangement and Work Safety on Road Works [TIEL 2270011]). The basic principle in temporary traffic control has been that each traffic arrangement will follow both the law and Finnra's guidelines. The basic problem always has been the attitudes of road users, Finnra's workers, and administrative personnel. The importance of temporary traffic control is not understood; on the contrary, many people think that "nothing will happen today because nothing happened yesterday." Finnra Road Administration has not paid enough attention to traffic and work zone safety during work on the road.

For Finnra Production, one of the site's staff typically takes care of the temporary traffic control in addition to other site work. This kind of system is still common among private companies, within Finnra Production's maintenance unit, and at small construction sites on the lower class road network. Typically, having 10 sites dealing with traffic control translates to 10 ways of interpreting the guidelines.

The question is also one of money, because all equipment costs money and is costly to maintain. The guidelines that Finnra Road Administration uses as a standard for temporary traffic control are not diverse enough to cover the whole country, which is why the range of quality in traffic control is so wide.

FIGURE 1 Organizational chart of the Finnish National Road Administration.

Subsequent to a decision made by the Finnish Parliament to separate the Finnish National Road Administration into a Road Administration unit and a Production unit (a state-owned enterprise), Finnra Production will compete for contracts with private contractors. In the near future, Finnra Production will receive most of its work through open competition, and one of its goals is to be able to compete on quality as well as on price.

Based on the low quality of the current guidelines, it is reasonable to expect that Finnra Road Administration will modify its contract documents to reflect the new situation. There are at least three reasons to clarify the expected quality of temporary traffic control in the standard contract papers:

- Finnra's goal to improve safety on construction sites;
- Finnra's division into Road Administration and Production units; and
- Out-of-date guidelines on temporary traffic arrangement, traffic safety, work safety, and the quality of these tasks.

Finnra Production realized that the only way to obtain a competitive advantage over the other contractors was to adapt to the new situation well in advance and to change its operation process, for example, by standardizing temporary traffic arrangement. Traffic arrangement was identified as a key competence of Finnra Production.

Since the late 1990s, for large projects located mostly in the surroundings of Helsinki or in road networks with heavy traffic, the responsibility for temporary traffic control has been assigned to one full-time employee. As a result, fewer than 10 people overall have become real experts in temporary traffic control.

Creating a Pilot Project for Traffic Control Services

To improve traffic safety in relation to temporary traffic control practices and to increase the quality of temporary traffic control during construction phases, a new scope of services was created in Finnra Production. It offers all-inclusive temporary traffic control services to anyone who needs them, both inside and outside Finnra, through a centrally organized traffic control team.

The pilot project started at the end of 1998. The project task force (steering committee) and follow-up group consist of five people: three from Finnra Production (the South Finland Production Area, the Research and Development Unit, and the Consulting Unit) and two from Finnra Road Administration (Central Administration and the Uusimaa Regional Administration). Information about the project also was regularly provided to the managers of contract units and the production areas of Finnra Production as well as other regional administrations.

The traffic control pilot team was set up to operate as an independent profit center of Finnra Production within the area of the Helsinki Contract Unit, but in response to demand, the operational area could be enlarged. Main clients of the traffic control team during the pilot phase were identified as Finnra Road Administration, other units of Finnra Production, local cities, municipalities, and private companies (such as electricity companies and other contractors). Figure 2 is the organizational chart (task force, pilot team, and clients).

The tasks relating to the core competence of the pilot team were identified as

- Preparing temporary traffic control plans,
- Creating the traffic arrangement,
- Renting equipment,
- Repairing equipment,
- Handling traffic arrangement during the construction phase, and
- Testing and developing new equipment under local conditions.

The basic principles of piloting the concept were to improve the safety and quality of temporary traffic control and to create a profitable service through a pioneer team for traffic and work safety services. The pilot team's four goals were to provide maximum safety to the road users, maximum safety to the workers, minimum delay on the construction site, and economy of traffic control.

SELECTING THE PILOT TRAFFIC CONTROL TEAM

The active phase of the pilot project was scheduled to last 7 months, from June through December 1999. During that time, the pilot team reviewed and developed its plan of action, selected a team leader for the pilot phase, and chose the specific test sections or jobs in which the process could be tested. The team also reviewed and mapped the costs of temporary traffic control services and conducted market research for its services. Part of this active phase was to decide what kind of operational system should be created to implement the concept starting in the beginning of 2000 and what kind of a report should be written about the experiences of the project's pilot phase.

In selecting the members of the pilot team, some qualifications were required to ensure the quality of the operational principles of the team. Each team member should be interested in traffic and work safety, be innovative, and like to work with traffic. In addition, each team member should be able to do almost any task required within the team's scope of services. The team members were trained on work and safety issues, specifically through a Finnra Road Administration training program.

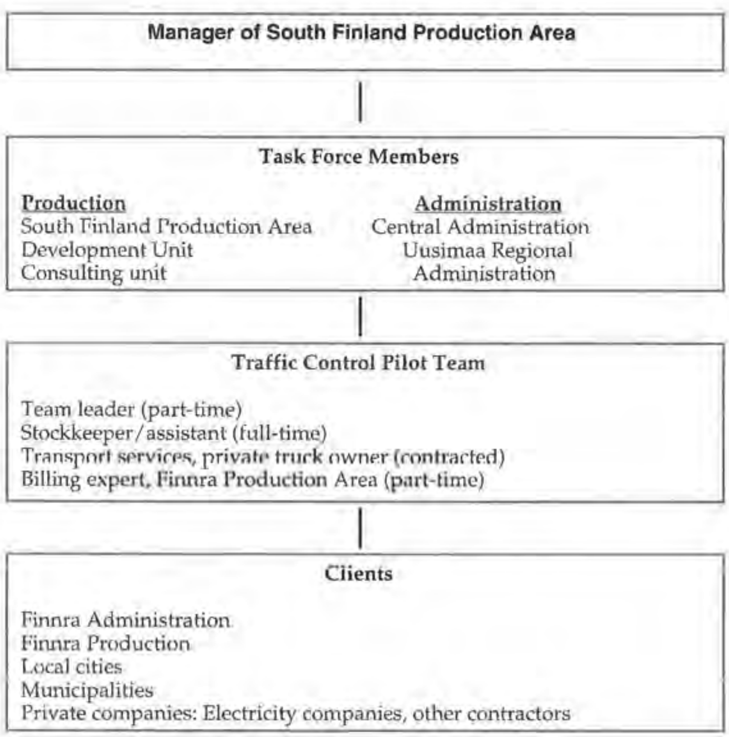

FIGURE 2 Organization chart of the task force, pilot team, and clients.

In 1997, the Finnra Board of Directors decided to create a systematic training program to improve the safety of road services. In 1998, Finnra Central Administration presented two training courses: Road Safety I and Road Safety II. Both courses end with a test that attendees must pass in order to obtain a certificate. Road Safety I is a one-day compulsory basic training course for everyone who works on the road. The topics cover the risks, the basics of traffic arrangement, and work safety. Road Safety II is a two-day training course aimed at technicians, engineers, and contract supervisors. The topics emphasize employer functions and the planning of work safety and traffic arrangement. Successfully completing Road Safety I is a prerequisite for taking Road Safety II.

As of the end of 1999, about 4,300 people (Finnra personnel and private contractors) had received the Road Safety I certificate (Figure 3 is an outline of the course). As of the end of 1999, about 100 people from Finnra had received the Road Safety II certificate. By April 1, 2003, all Finnra personnel and all outside contractors working on the road must have officially completed both standardized road safety training courses.

PILOT PHASE

During the pilot phase, the team contracted to work for Finnra Road Administration and Production at 26 work sites around Helsinki and in the Uusimaa region (Figure 4). The team also worked as a subcontractor for five private companies at 25 work sites in the Uusimaa region (Figure 4). The team and task force estimated that during the pilot phase, about 500 different work sites in the Uusimaa region required traffic arrangement. The team did not market its services; on the contrary, the team received all its work through negotiations or by word of mouth. We estimate that after the team has completed the operation process and fixed prices to the right level, the team can reach about 20 to 30 percent of market share.

The project's task force—acting as the follow-up group—wanted to keep the general costs of the pilot phase as low as possible. Therefore, the pilot team's organization was kept as light as possible. The team leader worked on both the pilot project and a regular road project for improving airport entrance roads; he contributed about 70 percent to the pilot project and 30 percent to the regular project. The stockkeeper/assistant was assigned to the team at the beginning of August 1999 but also worked with other Finnra units as much as possible. The required transport services were procured from a private truck owner, who worked for the team when needed. Billing was delegated to a billing expert from a Finnra Production area. The team leader had identified possible sources of deputy personnel, but the team managed to handle all tasks and work sites themselves.

1 RISKS IN WORKING ON THE ROAD

- 1.1 General
- 1.2 Danger caused by traffic
- 1.3 Danger caused by circumstances
  - 1.3.1 Perceiving the work area
  - 1.3.2 Factors that hinder perception
- 1.4 Worker risks
  - 1.4.1 Getting accustomed to risks and workplace blindness
  - 1.4.2 Poor perceptibility of workers
  - 1.4.3 Danger of machines
- 1.5 Danger to other road users
  - 1.5.1 Motor vehicle traffic
  - 1.5.2 Bicyclists, mopedists and motorcyclists
  - 1.5.3 Pedestrians
  - 1.5.4 Children
  - 1.5.5 Other road users
- 1.6 Problems of working
  - 1.6.1 Lack of space
  - 1.6.2 Material storage
  - 1.6.3 Workers' cars
  - 1.6.4 Hindrance caused by traffic
  - 1.6.5 Young, inexperienced workers

2 HOW DO I LOOK AFTER THE SAFETY OF OTHER ROAD USERS?

- 2.1 Basic principles of traffic arrangements at the work area
  - 2.1.1 Goals of traffic arrangements
  - 2.1.2 Implementation of traffic control
  - 2.1.3 Structure and erection of traffic signs
  - 2.1.4 Traffic signs needed in road work
  - 2.1.5 Barriers and warning devices
  - 2.1.6 Warning flashers
  - 2.1.7 Shielding the work area
- 2.2 Limiting speed
  - 2.2.1 Temporary speed limit
  - 2.2.2 Selection of a speed limit
  - 2.2.3 Repetition of a speed limit sign
  - 2.2.4 Emphasizing a speed limit
  - 2.2.5 Ending a speed limit
- 2.3 Working as a traffic director
- 2.4 Informing about road work
- 2.5 Operating machines in traffic
  - 2.5.1 General
  - 2.5.2 Working as a driver
  - 2.5.3 Caution when working on the road
  - 2.5.4 Exceptional regulations when operating a machine
  - 2.5.5 Warning devices

3 HOW DO I LOOK AFTER MY OWN AND OTHER WORKERS' SAFETY?

- 3.1 Looking after safety is part of professional skill
  - 3.1.1 Working on the road requires a high level of safety
  - 3.1.2 Safety is a part of work and work planning
  - 3.1.3 Workers' safety measures
  - 3.1.4 Workers' responsibilities and rights in job safety matters
  - 3.1.5 Getting acquainted with the work
- 3.2 Visible clothing and other personal protective equipment
  - 3.2.1 Visible clothing
  - 3.2.2 Other personal protective equipment and its use
- 3.3 Instruction and familiarization
  - 3.3.1 Providing instruction
  - 3.3.2 Information flow on the job
- 3.4 Instructions in case of an accident
  - 3.4.1 General responsibility to provide help
  - 3.4.2 General instructions in case of an accident
  - 3.4.3 Estimation of a situation
  - 3.4.4 Sequence of action
  - 3.4.5 Rescuing someone in danger
  - 3.4.6 Preparing for an accident in a work area
  - 3.4.7 Fire safety
- 3.5 Safe operation of machines and work equipment
  - 3.5.1 Looking after the condition of machines
  - 3.5.2 Daily operational tests
  - 3.5.3 Safe work procedures
  - 3.5.4 Watching out for equipment and structures in the road area

FIGURE 3 Finnra Road Safety I training course: outline of the training manual.

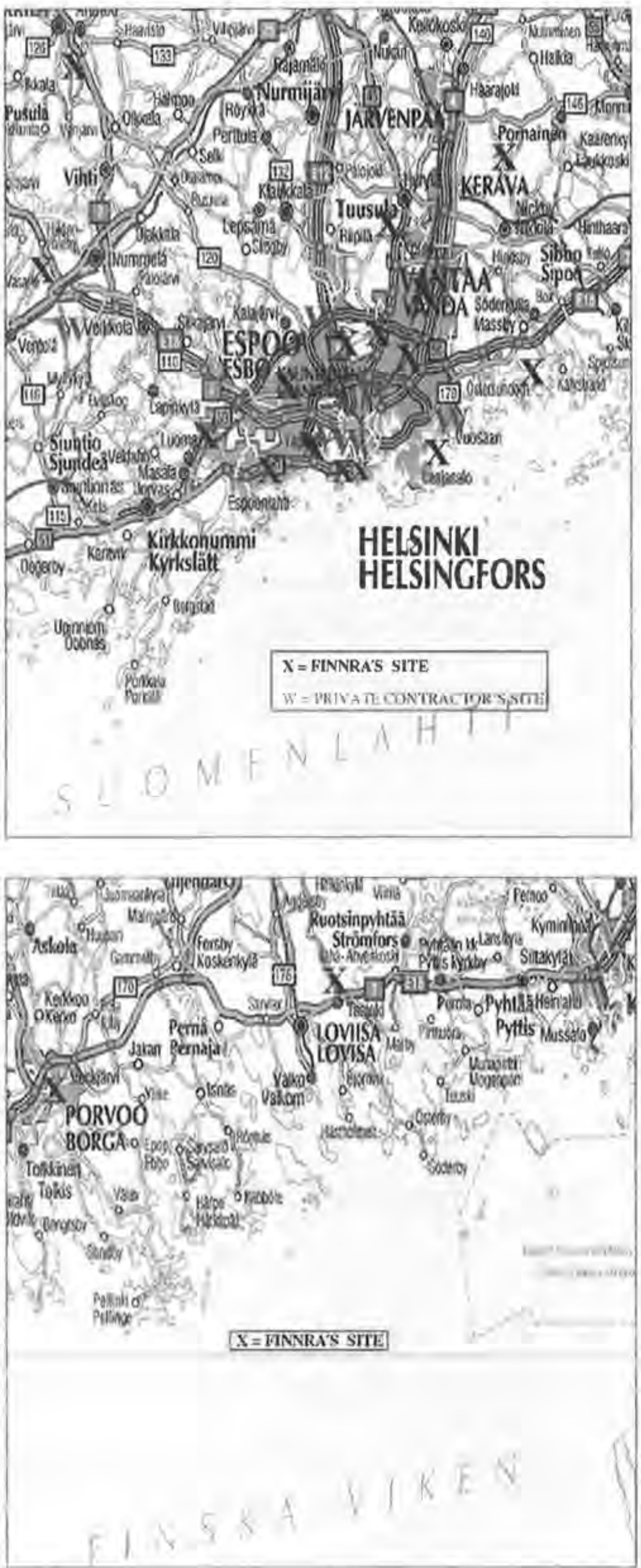

FIGURE 4 Maps of Helsinki and the Uusimaa region, Finland.

At the beginning of the pilot phase, the team leader made a list of all the necessary equipment and sent an invitation to bid to local equipment manufacturers and importers. He also made detailed agreements with other Finnra Production units and projects for allowing the pilot team and the Finnra Production units and projects to share some equipment at work sites. This cooperation would enable both the team and the units to organize and maximize the use of required equipment. The team was housed in a central location so that travel would be efficient and convenient for all members. The team leader organized a basic office space for the team's use with office tools and communication equipment (computer, fax, and so on).

The role of the team leader was to design and prepare plans for each work-site traffic control arrangement. He also took care of plan approval by the local road inspector and participated in carrying out the arrangement. Traffic control arrangement was well documented with a video camera or a still camera. Every time the team was on the road, the Uusimaa Regional Traffic Management Center was informed in the morning of the working day so that it could provide accurate information about temporary traffic control activities to the local radio stations or newspapers if necessary.

The members of the selected pilot traffic control team were committed to safe working methods, personal safety, and the use of efficient warning equipment. In doing their job, the team intended to seal off a working area as soon as possible. Achieving fluency of traffic flow and the safety of road users and workers was ensured by using clear paved driving routes, collision protectors, and other available safety equipment.

Costs

For implementing the pilot project, the team leader was authorized to spend up to 500,000 Finnish markka (Fmk 500,000/US$83,300) for procuring new or repairing old equipment. Out of this budget, the team spent Fmk 229,000 (US$38,200) on equipment procurement. The total costs of transport services were Fmk 181,000 (US$30,200). Personnel costs—including salaries, daily allowances, and reimbursements for using a personal vehicle—were Fmk 193,000 (US$32,200). The total earnings of the pilot traffic control team's work during the pilot phase were about Fmk 425,000 (US$70,800). The costs of the pilot project are summarized in Table 1.

The negative result of the pilot phase (a net loss) is attributable to the long-term procurement investments that could not reasonably be expected to be covered in 7 months and to insufficient marketing efforts. The follow-up task force did not want active marketing during pilot phase because the basic idea of the pilot phase

TABLE 1 Total Costs of Pilot Project During June–December 1999

	FIM	*$US*
Total expenses of the pilot project	**604,000**	**100,700**
• Procurement of traffic control equipment	229,000	38,200
• Transport services, contracted	181,000	30,200
• Personnel cost (salaries, daily allowance, etc.)	193,000	32,200
Total income of the pilot project	**425,000**	**70,800**
• Total earnings from work contracts	425,000	70,800

was to test and determine total expenses and see whether a market existed for this kind of service. The negative result in the budget was both anticipated and planned for at the start of the project; thus the follow-up group had accepted the negative result before the pilot phase had ended.

Experiences

The personnel involved in the pilot traffic control team during the pilot phase found most of their work interesting, flexible, and varied. The main reason for the positive attitude of the personnel appears to be that everyone was a volunteer for the project. The initial idea of creating the temporary traffic control team came from the pilot team leader, and he had actively participated in all the phases of the process. The team leader was personally allowed to interview for and then select the stock keeper and the truck contractor.

On the basis of customer surveys conducted, a true market exists for all-inclusive temporary traffic control services among outside contractors outside of Finnra Production. The in-house customers (i.e., other Finnra Production units) also were pleased to contract the traffic control services separately. The Production units realized that by using the traffic control team, they were able to concentrate on more critical work tasks. This situation in turn provided them an opportunity to further develop their core competencies and work more efficiently in their resource planning.

The customer surveys also revealed that clients found the price of the offered traffic control services rather expensive, which is quite a normal initial reaction to a new service. It is always difficult to accept the true cost of quality in the beginning. Another reason for not being able to easily relate to the standard cost of traffic control during a construction project is the fact that in Finland, the budgeting procedure for construction projects does not separate the cost of traffic control as its own item. To the pilot team leader, it became obvious that construction personnel were not aware of the cost of temporary traffic control because these costs usually were lumped with other costs resulting from general project services based on a percentage of the construction project's overall budget.

After the Pilot Phase

At the end of 1999, the pilot traffic control team was transformed into an official unit as part of the bridge group of the Helsinki Contract Unit. The team will work within the area of the Helsinki Contract Unit and then increase its working area as necessary. Also at the end of 1999, the manager of the South Finland Production Area assigned a new permanent leader for the traffic control team. The new team leader started by creating a comprehensive operational and quality process for the team's services. He also was challenged with forming the team's services into a product and completing the final report of the pilot phase.

The team leader created an operational and quality process for the team to present to the clients how the team plans to implement temporary traffic arrangement. A top-level outline of the operational and quality process is presented in Figure 5. Details cover, for example, quality demonstration, given in Paragraph 8.2: "Because of quality demonstration we have operational and quality file of every contract, into which we collect all the documents. The operational and quality file is in open view in our office. After the completion of the contract we will give one copy of the quality file to the client. During the contract we will keep a diary where

1. General
2. Resources of the team
    - 2.1 Personnel
    - 2.2 Point of support
    - 2.3 Material
    - 2.4 Machinery
3. Special tasks
4. Master plan of contract
5. Work and traffic safety
6. Environmental aspects
7. Information
8. Quality control
    - 8.1 Common quality control
    - 8.2 Quality demonstration
    - 8.3 Quality deviation
    - 8.4 Completing the contract
    - 8.5 Guarantee

FIGURE 5 Outline of the operational and quality process of the temporary traffic control team.

Finnish National Road Administration
PRODUCTION

TRAFFIC CONTROL SERVICES

CONTENT OF THE PRODUCT (Last updated 5.4.2000)

1. Design of temporary traffic arrangement
2. Implementation, dismount and maintenance of temporary traffic arrangement
3. Implementation, repairing and changing of traffic sign
4. Control of traffic arrangement and round the site during weekend
5. Design of temporary traffic lights
6. Implementation, maintenance and dismount of temporary traffic light
7. Rental of traffic signs, traffic control devices and traffic lights
8. Design of temporary road lighting

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1 **Design of Temporary Traffic Arrangements** (Last updated 4.4.2000)

Product description
- Product includes the design of temporary traffic arrangements. The detail of the design depends on the demands of the site.

Contents
- Team finds out work plans and schedule of the work from the client. The team finds out the daily traffic volume from Finnra Administration.
- The team visits the site to find out local conditions.
- During the site visit they decide on solutions of traffic arrangement.
- They make a detailed traffic arrangement design with Autocad. Design includes location map, design and specifications.
- They also add road markings and list of traffic signs to the design if client wants.
- minary approval to design from Finnra Administration or other authorities.
- They supply the design to the client.
- They ask for client feedback and develop product.

Clients' benefits
- Client gets specific traffic arrangement design.
- Road users get good service when traffic arrangement design is composed according to latest safety regulations and traffic regulations.
- Client does not have to tie up own personnel to design work.
- Client also gets quality facts and financing facts together with the design.
- With competent traffic arrangement design the client can ensure safety and flexible traffic through the site and also maximize the road capacity through the site. Maximizing road capacity also gives benefits to road users (for example: 200 m long detour on two lane road increases driving costs about 0.40 FIM/vehicle, when road capacity is not exceeded).

FIGURE 6 Finnra product description of the temporary traffic control team and one part of the product description (translated from Finnish).

we record all the details which might be relevant later on in order to show how we implemented the contract and the quality. We ensure the quality of materials with quality certificate of producer. We report on amount and quality of work according to how is stated in the contract documents."

The team leader also has drafted a product description that covers issues such as the kind of services the traffic control team offers to different clients. The table of contents of the product description of the temporary traffic control team and one part of the product description are translated as an example in Figure 6.

Investigation of Volume, Safety, and Vehicle Speeds During Winter Storm Events

Keith K. Knapp

Winter storm events can have significant impacts on mobility and safety. During the past year, these impacts were investigated by the Center for Transportation Research and Education of the Iowa Department of Transportation. The documented project proceeded in two phases. First, data related to traffic flow, crashes, weather, and roadway conditions were collected from existing information management systems in Iowa; these data were evaluated and analyzed. Second, a mobile video data collection system was used to collect data during seven winter storm events. The results from both phases of this project are summarized.

Traffic volume, safety, and vehicle speed along a roadway segment are functions of several factors (e.g., percentage of heavy vehicles, lane widths). One of these factors is weather. Engineering designs and maintenance attempt to minimize the effects of weather on traffic, but each year winter storm events affect mobility and safety.

This research used data from several existing Iowa information management systems as well as traffic flow and roadway condition data collected from a mobile video data collection system. These data were analyzed to evaluate winter weather impacts on traffic volume, safety, and vehicle speeds.

Civil and Construction Engineering, Center for Transportation Research and Education, Iowa State University, 2901 South Loop Drive, Suite 3100, Ames, IA 50011.

Literature Review

Weather and Volume

Hanbali and Kuemmel investigated traffic volume reductions during winter storms (*1*). They collected traffic volume and weather data from at least the first 3 months of 1991 at 11 locations in four states. Traffic volume reductions were calculated for different ranges of total snowfall, average daily traffic, roadway type, time of day, and day of the week. Overall, the reductions ranged from 7 to 56 percent. The researchers concluded that volume reductions increased with total snowfall but that the reductions were smaller during peak travel hours and on weekdays. A 1977 FHWA study had similar findings (*2*).

Weather and Safety

Several researchers have explored the relationship between adverse weather and safety (*2–7*). For example, Hanbali found a significant decrease in crash rates before and after deicing maintenance activity (*3*), and the results of three Swedish studies support these findings (*4–6*). The Swedish studies also indicate that severe injury rates on roads with snow and ice can be several times greater than on roadways during any other time of year (*4–6*). Perry and Symons found that total injuries and fatalities increased by 25 percent on snowy days, and the rate of injuries and fatalities increased by 100 percent (*7*). A Canadian study, on the other hand, reported higher minor and material damage accident rates but lower severe and fatal crash rates in the winter months (December to March, inclusive) than in the summer months (*4*). A 1977 FHWA study had similar findings but found that the rates of severe injury crashes were increased in snowbelt states over the nonsnowbelt states during winter months (*2*).

Weather and Speed

One measure of traffic flow mobility is vehicle speed. In an economic analysis of winter weather maintenance, Hanbali used a FHWA study that found an average range of speed reduction due to snow and ice conditions of 18–42 percent on two-lane roadways and 13–22 percent on freeways (*2, 3*). A Swedish study [referenced by Brown and Baass (*4*)] also found a reduction in speed of 10–30 percent with ice and snow conditions (*8*). However, another study concluded that speed reductions might be determined more by roadway appearance than the actual friction levels provided and that the speed reductions observed were typically higher when slippery roadway conditions were combined with precipitation (*9*).

Other studies have categorized weather events and evaluated their effect on operating free-flow vehicle speeds. For example, Lamm et al. considered 24 rural two-lane highways under dry and wet conditions but found no statistical difference in operating speed (*10*). However, visibility was not limited during any of the rain events considered. On the other hand, Ibrahim and Hall found site-specific reductions in free-flow speed of 1.9 km/h (1.2 mph) for light rain, 3.1 km/h (1.9 mph) for light snow, 5.0–10.0 km/h (3.1–6.2 mph) for heavy rain, and 38.0–49.9 km/h (23.6–31.0 mph) for heavy snow (*11*). These data should be used with caution, because they may represent the effects of other data collection site characteristics. In a German study, Brilon and Ponzlet found a vehicle speed reduction of 9.5–11.9 km/h (5.9–7.4 mph) when roadways were wet (*12*). Finally, there are also several proposals for the inclusion of currently unpublished speed/weather relationship data within the *2000 Highway Capacity Manual*. Ongoing studies show that light precipitation and heavy rain may have larger impacts on free-flow speed than previously documented and that high winds also may have an influence.

The effects of visibility on vehicle speed also have been considered. Liang et al. studied a 24-km (15-mi) segment of Interstate Route 84 in Idaho from December 1995 to April 1996 (*13*). During this time, extreme weather conditions were observed on 21 days. The speed data from foggy days revealed an average speed reduction of 8 km/h (5 mph) compared with average speeds on clear days. The data from days with snow, on the other hand, showed that speeds were affected by more than visibility. A generalized linear model described speed as a function of visibility, snow cover, light, temperature, and wind. Overall, an average speed reduction of 19.2 km/h (11.9 mph) was observed during snow events, but the data were highly variable. Liang et al. concluded that the measured speed reductions resulted from a perceived reduction in safety by drivers (*13*).

DATA COLLECTION

For the first phase of this project, data were collected from a roadway weather information system (RWIS), automatic traffic recorders (ATRs), an accident location and analysis system (ALAS), and the Iowa Department of Agriculture and Land Stewardship (IDALS)/National Weather Service (NWS). The roadway and/or weather data from Iowa RWIS stations and the IDALS/NWS, crash data from ALAS, and hourly traffic volumes from Iowa interstate ATRs were linked. These data were acquired for both winter storm events and comparable non–storm events.

Overall, seven RWIS sites along the Iowa interstate were analyzed during the first phase of this project. All of the RWIS stations had a nearby ATR, and the hourly volumes collected at these ATRs were used to approximate storm event and non–storm event traffic volumes adjacent to the RWIS station. The locations of the seven RWIS/ATR pairs are shown in Figure 1. Bidirectional ATR hourly traffic volumes were acquired for 1995, 1996, 1997, and 1998, but the data were not used if estimated (due to an ATR malfunction) or measured on a day near a holiday (i.e., an atypical travel day).

Weather and roadway data from the RWIS stations (Figure 1) and daily snowfall information from IDALS/NWS observer sites were used to define, identify, and determine the time periods when winter storm events most likely occurred. RWIS and IDALS/NWS data from all or part of the 1995–1996, 1996–1997, and 1997–1998 winter seasons were acquired. In general, *winter storm event time periods* were defined as those hours when the RWIS stations recorded four kinds of data:

- Precipitation occurring,
- Air temperature below freezing,
- Wet pavement surface (indicated at any of the pavement sensors at the site), and
- A pavement temperature below freezing (indicated at all of the pavement sensors at the site).

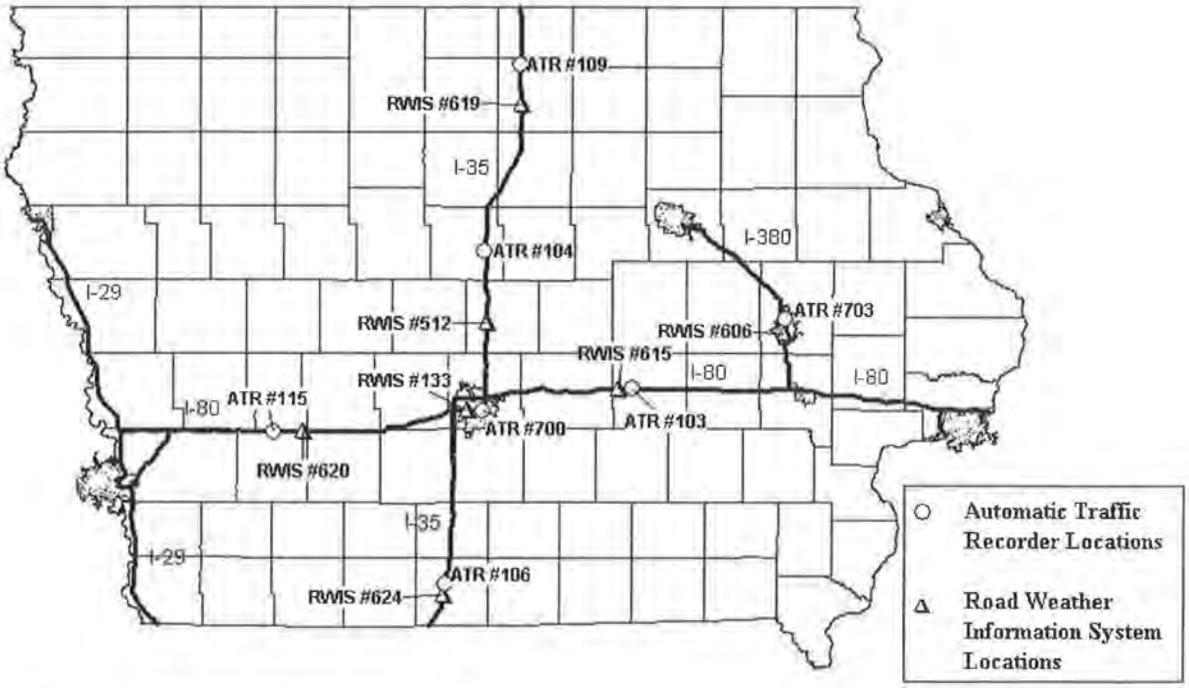

FIGURE 1 Data collection sites selected.

Any two winter storm events (as defined above) separated by only one "nonstorm" hour were combined. In addition, this research considered only those winter storm event time periods that had a duration of at least 4 h and an estimated snowfall intensity (from nearby IDALS/NWS information) of 0.50 cm/h (0.20 in./h). The goal was to limit the research analysis to relatively significant winter storm events.

For the second phase of this project, traffic flow, weather, and roadway condition data were collected. Data were collected with a mobile video traffic data collection system (commonly known as an AutoScope) during seven 1998–1999 winter storm events. The safety of the data collection team and an ability to respond quickly to approaching winter storm events were the determining factors in selecting the data collection site.

First, it was decided that the data collection equipment and personnel should not be adjacent to the interstate roadway during winter storm events and that the data should be collected from a low-volume bridge that overpasses Interstate Route 35. Second, the data collection location needed a bridge width of at least 8 m (26 ft) to allow two-way traffic flow during the data collection activities. Finally, the site had to be close to the data collection team based in Ames, Iowa. The amount of time needed to assemble the team and to prepare and set up the equipment was relatively significant (i.e., hours). The site chosen was Northeast 142nd Avenue in Polk County, Iowa. This roadway crosses over Interstate Route 35 about 16 km (10 mi) south of Ames.

Winter Storm Event Impact Analysis

Volume Analysis

Overall, 64 winter storm events, totaling 618 h, were defined for the traffic volume analysis. Some descriptive statistics of the percent volume reductions during winter storm events are shown in Table 1. The traffic volume effects of winter storm events vary widely. The average storm event volume reduction (by location) ranges from approximately 16 ($n = 10$) to 47 percent ($n = 6$), and the overall average volume reduction is approximately 29 percent. The 95 percent confidence interval for the overall average percent volume reduction is 22.3–35.8 percent. The variability in the data is also shown by the fact that the standard deviation of the percent volume reduction at each RWIS location is about the same as the average percent volume reduction at that location.

Regression analysis (assuming a normal distribution of the data) was used to investigate the relationships between percent volume reduction (the dependent variable) and storm event duration, snowfall intensity and total snowfall, minimum and maximum average (during a 1-min period) wind speed, and maximum gust wind speed (maximum 4-s wind speed during a 1-min time period). The regression analysis indicated that percent volume reduction has a positive and statistically significant relationship with total snowfall and the square of maximum gust wind speed. The other variables considered

TABLE 1 Traffic Volume Summary for Winter Storm Events

Interstate RWIS Location	Number of Storm Events	Storm Event Hours	Average Storm Event Volume Reduction (Percent)	Std. Dev. Storm Event Volume Reduction (Percent)	Min. Storm Event Volume Reduction (Percent)	Max. Storm Event Volume Reduction (Percent)
#133 – I-235, Des Moines	8	83	36.4	30.5	13.0	86.5
#512 – I-35, Ames	10	82	15.5	13.7	1.4	46.9
#606 – I-380, Cedar Rapids	4	70	23.7	18.9	0.8	40.0
#615 – I-80, Grinnell	6	71	46.9	46.2	-42.1	84.3
#619 – I-35, Mason City	12	79	19.1	20.1	-1.9	71.6
#620 – I-80, Adair	10	107	35.3	30.8	-8.0	91.5
#624 – I-35, Leon	14	126	32.5	23.1	5.5	80.8
Overall	64	618	29.1	26.7	-42.1	91.5

NOTE: Negative volume reductions indicate an increase in volumes. Overall, three of the storm events defined had negative volume reductions.

were either correlated with these two variables or were not found to have a statistically significant relationship with percent volume reduction. The results of the regression analysis are shown in Table 2. Summary statistics of the model indicate a significance at a 95 percent level of confidence, and an adjusted coefficient of multiple determination (i.e., R^2) of 54.4 percent.

Safety Analysis

Overall, 54 winter storm events, totaling 491 h, were defined for the crash analysis. Information for crashes that occurred during the winter storm event time periods was acquired from ALAS for a 48-km (30-mi) Interstate highway section adjacent to and centered on each of the RWIS locations shown in Figure 1. Hourly traffic volumes for the same time periods were approximated from nearby ATRs. It was assumed that in most cases, a segment of this length would experience the same type of weather conditions.

As expected, both the number of crashes and the crash rate increased during winter storm events. On average, 2 crashes were reported during each winter storm event and 0.65 crashes during comparable non–storm event time periods. This non–storm event average, however, represents a combination of the non–storm event hours for all the similar days during the same month as the comparable storm event time period (i.e., it is based on a longer duration of time). In fact, the hourly crash frequency increased by about 942 percent during the winter storm events considered. In addition, this increase in crashes—and the typical decrease in traffic volumes—produced about a 1,300-percent increase in crash rate during the winter storm events considered.

A Poisson regression modeling approach was used to analyze crash frequency. The crash frequency during winter storm events was the dependent variable, and the independent variables included exposure (i.e., million vehicle miles), snow event duration, snowfall intensity, maximum gust wind speed, maximum average wind speed, and minimum average wind speed. Table 3 shows the Poisson modeling results. The model indicates significantly positive coefficients for exposure, snow event duration, and snowfall intensity. In other words, increased exposure, snow event duration, and snowfall intensity increase the predicted crash frequency during a winter storm event. The model was constructed to indicate the impact of winter storm event duration beyond the effect already captured by the exposure term.

Speed Analysis

The second phase of this research project involved collecting traffic flow, roadway, and weather-related data during seven 1998–1999 winter storm events. During these events, there was some kind of snowfall (e.g., light, moderate, or heavy), and in most cases, winter maintenance activities were taking place. The data collected and

TABLE 2 Regression Analysis Results, Traffic Volume During Winter Storm Events (Dependent Variable: Percent Winter Storm Event Volume Reduction)

Explanatory Variable	Coefficient	T-Statistic	P-Value	Mean of Variable	Std. Dev. of Variable	Range of Variable
Total Snowfall (inches)	2.289	2.16	0.035	3.764	2.377	1.05 to 10.83
Max. Gust Wind Speed (mph)	0.0296	6.87	0.000	742.7	584.1	36.0 to 2,916.0
Constant	-1.583	-0.35	0.730	–	–	–

NOTE: mph = miles per hour. 1 in. = 2.54 cm; 1 mph = 1.61 km/h. Model Summary Statistics: Number of Observations = 64; F-Value = 38.65; P-Value = 0.000; Mean Square Error = 332; Coefficient of Multiple Determination = R-Squared = 0.559; and R-Square (Adjusted) = 0.544.

TABLE 3 Poisson Model Regression Results, Crash Frequency During Winter Storm Events (Dependent Variable: Crash Frequency During Snowstorms)

Explanatory Variable	Coefficient	T-statistic	Marginal Values	Mean of Explanatory Variable
Exposure (mvm)	0.682	6.148	0.832	0.341
Snowstorm duration (hrs)	0.156	5.826	0.190	9.093
Snowfall intensity (inches/hr)	0.494	2.226	0.603	1.068
Max wind gust speed (mph)	0.009	1.311	0.010	37.540
Constant	-2.315	-5.142	-2.826	-

NOTES: mvm = million-vehicle-miles; mph = miles per hour; 1 mi = 1.61 km. Model Summary Statistics: Number of Observations = 54; Log likelihood function [L(β)] = –84.314; Restricted Log likelihood [L(0)] = –151.546; and $\rho^2 = 1 - L(\beta)/L(0) = 0.443$.

summarized into 15-min increments included traffic volumes, vehicle speeds, vehicle gaps and headways, visibility [more than or less than 0.40 km (0.25 mi)] and roadway snow-cover conditions (snow on the roadway lanes or only the shoulders). Some of the data were collected manually, but all of the traffic flow data (e.g., volume, speed, headway, and gaps) were collected with mobile video data collection equipment (i.e., the AutoScope). Overall, 109 15-min time periods (approximately 27 h) of data were collected during the seven winter storm events. In addition, for comparison purposes, the same kinds of data were collected on a typical weekday in May, in the absence of adverse weather and roadway conditions.

The summary statistics for all the data collected during phase two of this project are shown in Table 4. Data are summarized for each winter storm event, the overall database, and the normal weekday. General relationships among average vehicle speeds, traffic volumes, vehicle gaps, roadway condition, and visibility during winter storm events appear to exist. For example, as weather and roadway conditions worsen, traffic volume decreases and vehicle gaps (i.e., the average vehicle density) increase. Not surprisingly, average vehicle speeds during winter storm events also generally decrease as weather and roadway conditions worsen. For this reason, Table 4 generally shows a decrease in average vehicle speeds during winter storm events as the volumes decrease. In addition, the average vehicle speeds during winter storm events also appear to decrease with visibility, roadway conditions, or some combination of the two.

The vehicle speeds measured during the winter storm events were lower than typical non–snow speeds at the data collection site. Overall, the average 15-min vehicle speeds during the seven winter storm events (Table 4)

TABLE 4 Variable Mean of Data for Winter Storm Events

Winter Storm Event Date	Sample Size[1]	Mean Vol. (vph)[2]	Mean Factored Vol. (vph)[2]	Mean Gap (sec.)[3]	Std. Dev. of Gap (sec.)	Range of Gap (sec.)	Mean Percent Snow Covered Rdwy.[4]	Std. Dev. of Percent Snow Covered Rdwy.	Range of Percent Snow Covered Rdwy.	Visibility over ¼-mile?[5]	Mean Speed (mph)	Std. Dev. of Speed (mph)	Range of Speed (mph)
Wed., Dec. 30, 1998	22	747	810	4.6	1.9	2 to 9	40%	0.0%	40% to 40%	16	63.6	4.8	53.0 to 69.5
Sun., Jan. 17, 1999	8	727	1,296	4.8	0.46	4 to 5	0.0%	0.0%	0.0% to 0.0%	7	69.7	0.60	68.9 to 70.5
Fri., Jan. 22, 1999	7	990	1,100	3.9	1.2	3 to 6	0.0%	0.0%	0.0% to 0.0%	4	63.8	6.33	54.7 to 70.7
Thurs., Feb. 11, 1999	19	541	590	6.8	1.7	6 to 13	21%	25%	0.0% to 50%	12	55.4	8.23	43.6 to 66.9
Thurs., Feb. 18, 1999	15	419	473	8.8	1.2	7 to 11	7%	8%	0.0% to 15%	15	61.5	1.34	59.4 to 63.5
Mon., Feb. 22, 1999	16	798	900	4.9	2.1	3 to 12	11%	29%	0.0% to 85%	16	63.7	4.38	52.6 to 67.0
Mon., Mar. 8, 1999	22	161	174	28.5	15.8	11 to 68	53%	27%	15% to 90%	12	51.3	4.88	45.3 to 62.6
Overall Winter Storm Event	109	569	662	10.4	11.7	2 to 68	25%	27%	0.0% to 90%	82	59.9	7.57	43.6 to 70.7
Normal Dry Weekday (Wed. May 19, 1999)	46	1,037	1,037	3.7	0.91	2 to 5	–	–	–	–	71.5	1.86	68.3 to 75.1

NOTES: vph = vehicles per hour, sec. = seconds; mph = miles per hour; 1 mi = 1.61 km.

[1]Sample size is the number of 15-minute time periods in winter storm event.

[2]Mean volumes are for two lanes, and not factored. Factored volumes are for proper comparison to volumes on a non-storm event Wednesday in May.

[3]Gap equals time period between vehicles traveling in both lanes.

[4]Mean percent snow covered roadway is an estimation of the roadway cross section (including shoulders) covered by snow (in percent) during a particular 15-minute time period. Forty percent and below typically represents snow covering the shoulders only.

[5]Visibility number represents those periods with visibility over ¼ mile.

ranged from 70.2 to 113.8 km/h (43.6 to 70.7 mph), and the mean vehicle speed for each winter storm event ranged from 82.6 to 112.2 km/h (51.3 to 69.7 mph). In addition, the standard deviation of the average vehicle speed during winter storm events ranged from 0.97 to 13.25 km/h (0.60 to 8.23 mph). Overall, the average vehicle speed during winter storm events was approximately 96.4 km/h (59.9 mph) and had a standard deviation of 12.18 km/h (7.57 mph) ($n = 109$). During a normal weekday, on the other hand, the average vehicle speed was approximately 115.1 km/h (71.5 mph) with a standard deviation of only 2.99 km/h (1.86 mph) ($n = 45$). This difference is about 16 percent among the normal and average vehicle speeds during winter storm events, and this reduction is significantly different from 0 at a 95-percent level of confidence. The standard deviations of the normal and average vehicle speeds during winter storm events also were substantially different.

Past research has shown that peak-period travel decisions are based on a different set of criteria than vehicle trips taken during off-peak travel periods. During phase two of this research, 90 of the 109 15-min time periods for data collection were during off-peak travel periods (i.e., not between 4 and 6 p.m.). Therefore, the statistical modeling in phase two was limited to the data collected during the off-peak time periods. The amount, variability, intercorrelation of the data collected (e.g., the range of characteristics exhibited by the seven winter storm events observed), and the number of factors that can affect average vehicle speeds during winter storm events generally limit the explanatory power of the off-peak model developed.

Regression analysis (assuming a normal distribution) was used to evaluate and quantify the apparent relationships between off-peak average vehicle speed during winter storm events and the other data collected. A statistically significant relationship was found between the off-peak average vehicle speeds during winter storm events and the square of traffic volume (an apparent surrogate for weather variables not collected in phase two), a visibility index [more than or less than 0.40 km (0.25 mi)], and a roadway condition index (snow on the roadway lanes or only the shoulders). The results of the regression analysis are shown in Table 5 and Figure 2. However, the analysis included only those 15-min time periods with at least 30 vehicles (i.e., 30 speed measurements available). This requirement reduced the number of data points by seven (i.e., $n = 83$), and the seven time periods removed from consideration may have represented the most severe weather conditions. The requirement also increased the reliability of the model results by limiting the minimum number of individual vehicle speeds on which each average data point (Figure 2) was based. Although the results of the statistical analysis are useful overall, they still should be used with caution.

Several conclusions can be reached from the model developed (Table 5, Figure 2). The relationship between the off-peak average vehicle speed during winter storm events and the square of traffic volume appears to be a surrogate for weather factors that could not be collected during this phase of the research. In fact, phase one indicated that traffic volume reductions during winter storm events were related to total snowfall and the square of maximum gust wind speed. These two weather variables were not collected during phase two, but they would appear to have at least an indirect effect on the off-peak average vehicle speed during winter storm events (through the traffic volume variable).

The model also indicates that visibility below 0.40 km (0.25 mi) reduces the predicted average vehicle speed during winter storm events by approximately 6.3 km/h (3.9 mph). The encroachment of snow on the roadway lanes (i.e., the roadway condition index), on the other hand, reduces the predicted average vehicle speed during winter storm events by about 11.6 km/h (7.2 mph). Therefore, a combination of poor visibility and roadway conditions can decrease average vehicle speeds during winter storm events by about 18 km/h (11 mph). However, the relationships quantified among average vehicle speed, visibility, and roadway cover during winter storm events are based on a small amount of data ($n = 19$ and $n = 10$). Overall, the model does have some explanatory

TABLE 5 Regression Analysis Results: Average Vehicle Speed During Winter Storm Events, Off-Peak and No Low-Volume Time Periods (Dependent Variable: Average Vehicle Speed, in mph)

Explanatory Variable	Coefficient	T-Statistic	P-Value	Mean of Variable	Std. Dev. of Variable	Range of Variable
Traffic Volume*Traffic Volume (vph)	0.00002	7.91	0.000	327,980	214,125	15,376 to 788,544
Visibility Index[1]	−3.88	−3.08	0.003	—	—	—
Roadway Cover Index[2]	−7.23	−4.28	0.000	—	—	—
Constant	55.7	52.90	0.000	—	—	—

NOTE: mph = miles per hour; vph = vehicles per hour; 1 mi = 1.61 km.

[1]The visibility index is equal to one when visibility is less than ¼ mile and zero when greater.

[2]The roadway cover index is equal to one when snow has begun to impact the roadway lanes and zero if snow is only on the shoulders or nonexistent on the roadway surface.

Model Summary Statistics: Number of Observations = 83; F-Value = 42.55; Mean Square Error = 21.85; P-Value = 0.000; Coefficient of Multiple Determination = R-Squared = 0.618; and R-Square (Adjusted) = 0.603.

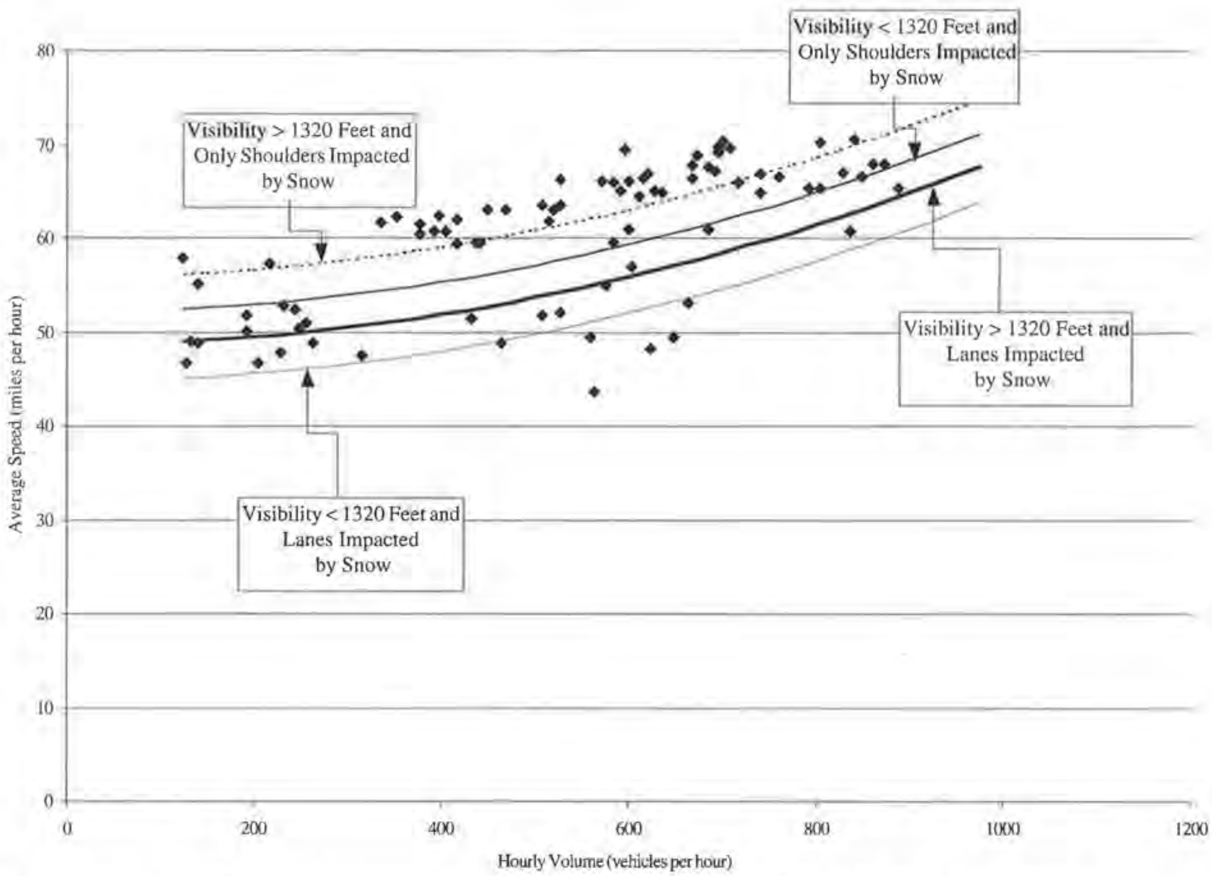

FIGURE 2 Off-peak average speed model for winter storm events (1 mph = 1.61 km/h; 1 ft = 0.3048 m).

power with an adjusted coefficient of determination (R^2) of approximately 60 percent.

Summary of Findings

The 64 winter storm events used in the traffic volume analysis reduced volumes by an average of approximately 29 percent, but the reduction was relatively variable. In addition, the 54 winter storm events used in the crash analysis had an overall hourly crash frequency increase of about 942 percent and a crash rate increase of approximately 1,300 percent.

The traffic volume regression analysis indicated a significant relationship among percent volume reduction, total snowfall, and the square of maximum gust wind speed during winter storm events. The crash regression analysis found a significant relationship between crash frequency, exposure (million vehicle miles), event duration, and snowfall intensity during winter storm events.

Two factors could be responsible for the difference between the crash rates for winter storm events and non–storm events. First, the definition of *winter storm event* used in this study is "relatively severe weather conditions under which the likelihood of crashes could be very high." Second, under severe weather conditions and the extended duration of a winter storm event, traffic volumes tend to reduce appreciably. With substantially reduced traffic volumes, the occurrence of only a few crashes can result in substantial crash rates.

The seven 1998–1999 winter storm events during which data were collected had a wide range of characteristics. Conditions ranged from extremely poor conditions [e.g., snow falling, but visibility less than 0.40 km (0.25 mi) and 90 percent of the roadway cross section covered by snow] to near-normal conditions [e.g., snow falling, but no snow on the roadway and visibility more than 0.40 km (0.25 mi)]. In fact, the mean vehicle speed for the seven individual winter storm events ranged from 82.6 to 112.2 km/h (51.3 to 69.7 mph). Overall, the average vehicle speed during winter storm events was 96.4 km/h (59.9 mph), but the normal (or non–snow event) average vehicle speed was 115.1 km/h (71.5 mph). This difference represents a 16 percent reduction in average vehicle speed between normal and winter storm event conditions. The standard deviation for the average vehicle speeds during the winter storm events also was 12.18 km/h

(7.57 mph), but for the normal (or non–snow event) conditions, it was 2.99 km/h (1.86 mph). Therefore, average vehicle speeds are not only reduced during winter storm events but also more variable than during non–snow events.

A multiple regression analysis (assuming a normal distribution of the data) of the data collected during the 1998–1999 winter season was also completed. The focus of the analysis was the off-peak data for winter storm events. Relationships among average vehicle speed, traffic volume, vehicle headway and gap, visibility, and roadway snow cover during winter storm events were evaluated. A relationship (within 95 percent level of confidence) was found among average vehicle speed, the square of traffic volume, visibility [more than or less than 0.40 km (0.25 mi)], and roadway snow cover (snow on the roadway lanes or only the shoulders) during winter storm events.

Overall, average vehicle speed during winter storm events increased with the square of traffic volume and decreased when visibility dropped below 0.40 km (0.25 mi) and when snow began to cover the roadway lanes. It is believed that the traffic volume variable in this model is a surrogate for other weather characteristics that affect vehicle speed but could not be collected during the 1998–1999 winter season (e.g., total snowfall and wind speeds). The model indicates that visibility less than 0.40 km (0.25 mi) decreases average vehicle speed during winter storm events by about 6 km/h (4 mph), and that snow on the roadway lanes decreases it by about 11 km/h (7 mph). Both of these reductions in average vehicle speed were found to be statistically significant at a 95 percent level of confidence. However, because of the small data sets used to make these conclusions ($n = 19$ and $n = 10$), caution is advised with their application.

A combination of the results found in this research and comparable winter weather vehicle speeds could eventually be used to determine a customer-impact-based winter weather level of service. Relationships among volume, speed, and weather and roadway conditions would need to be defined and/or established. The speeds for specific roadway or weather conditions might be acquired from past research, ATRs, and possibly the application of video-based data collection equipment. However, speed and volume data would need to be collected and archived, and weather and roadway conditions defined and correlated with these traffic flow characteristics.

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The contents of this paper reflect the views of the author, who is responsible for the opinions, findings, and conclusions presented herein. They do not necessarily reflect the official views or policies of the Iowa Department of Transportation or the Iowa Highway Research Board.

Winter Maintenance Standards on Cycleways

Anna Bergström

A high incidence of bicycle usage for personal travel is desirable, provided it is associated with a corresponding decrease in car-based transport. Cycling provides considerable health benefits as well as environmental benefits. During winter, weather conditions figure significantly in a person's decision whether to cycle; whereas road conditions are also important, it is not certain that improved road standards would increase cycling usage. The relationship between improved winter maintenance standards and the benefit to society is complex and merits additional study. During February and March 1999, a pilot study of unconventional methods for snow clearance and skid control was performed in Linköping, Sweden. One method with good results involved a front-mounted sweeper for snow clearance combined with a brine spreader for deicing. This method was further tested in a large-scale field study during the winter of 1999–2000. Both of these studies are presented, with the main focus on how to evaluate road standards (for example, through observation of road conditions and friction measurement). Literature reviews concerning winter maintenance methods for cycleways used in Sweden are also included. Winter maintenance methods on cycleways used today often are adapted to the prevailing conditions on motor traffic roads but are not necessarily the best methods for bicycle traffic. The methods most suitable for cycleways with regard to accessibility and total cost for cyclists are needed. A combination of different methods adjusted to weather and road conditions is likely to be the best solution.

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A high incidence of bicycle usage for personal travel is desirable, assuming it is associated with a corresponding decrease in car-based transport. A reduction of motor traffic, especially in urban regions, would be desirable for environmental reasons. Cycling provides considerable health benefits (*1*).

In Sweden, cycling is an increasingly important mode of transport. Of all passenger journeys in Sweden, approximately 11 percent are made by bicycle and 59 percent are made by car (*2*). Nevertheless, the transport mileage by bicycle is only 3 percent compared to 84 percent by car. Of course, cycling frequency varies between cities due to tradition, attitudes, climate, and topography. Even though cycling for personal travel in Sweden is considered significant compared with many other western countries, the potential for further increasing cycling frequency is high. Most people consider that cycling distances less than 5 km present no difficulty, but approximately 60 percent of all passenger journeys in Sweden are shorter than 5 km, and just over 50 percent of these journeys are made by car. Cycling could increase in response to campaigns that influence peoples' attitudes toward cycling, restrictions for motor traffic, and other means.

Even during winter, bicycles are used for personal travel in Sweden. However, the variation in cycling frequency between seasons is large, and the cycling frequency during the summer is nearly three times higher than during the winter (*3*). The decrease in winter cycling frequency is probably largely due to less favorable weather conditions; low temperatures, strong winds, ice, and snow affect cycling frequency negatively (*4*). Not only current conditions are significant in this respect; weather on the days immediately preceding travel also affects a person's choice of transport mode (*5*).

Road conditions also are important in deciding whether to cycle (*6, 7*). However, it is not certain that an improved winter maintenance standard for cycleways could increase cycling frequency during winter. If it could, then how large is the potential for winter cycling? How can the road standard be improved, and what will it cost? Road conditions are also important for the safety of cyclists. Many single accidents are caused by hazardous road conditions (*3, 8–11*). With dry surface conditions, the chief causes of accidents are ruts, unevenness, and cracks in the surface or sand, gravel, and other debris; during winter, the risk of accident is increased by ice and snow. Obviously, improved winter maintenance standards and benefits to society form a rather complex relationship. Figure 1 is an attempt to portray this relationship. Note that if the directed edges in the graph are quantified, it is possible to carry out cost/benefit analysis for improved winter maintenance standards.

Additional studies (questionnaire surveys, interviews, and field studies) are needed to determine whether it is possible to increase cycling frequency during winter just by improving the winter maintenance standards on cycleways. Field studies include bicycle counts related to different road conditions and comparisons of road standards achieved with altered methods. However, before these field studies can be done, methods for comparing different road conditions on cycleways are needed. It also is important to define good road standards on cycleways from a cyclist's point of view.

Purpose

In this paper, a method is presented for describing winter road conditions on cycleways that will be easy to use for comparing studies and that clearly describe the prevailing conditions. A review of field studies where road conditions on cycleways in Linköping, Sweden, were observed during the use of unconventional methods for snow clearance and deicing is included. Another objective is to present a short review of winter maintenance methods for cycleways normally used in Sweden.

Methods

The content of this paper is based on literature reviews and field studies. Literature reviews were conducted to find methods for describing winter road conditions on cycleways and to overview present winter maintenance methods for cycleways. Field studies were conducted mainly to obtain appropriate ideas for improving the available observation methods.

Maintenance and Operation of Cycleways in Sweden

Snow Clearance

Snow plowing is the method usually used for clearing snow from cycleways in Sweden as well as in Norway, Finland, and Denmark (*12*). Other methods include the use of snowblowers or mechanical sweepers, although these methods are seldom used.

The methods and equipment used for cycleway maintenance are the same as for roadways. However, the large, heavy equipment can cause damage to cycleways and has difficulty passing through tunnels and narrow passages. Its usability is also reduced to a certain degree by low speed. Examples of vehicles specially adapted for paths

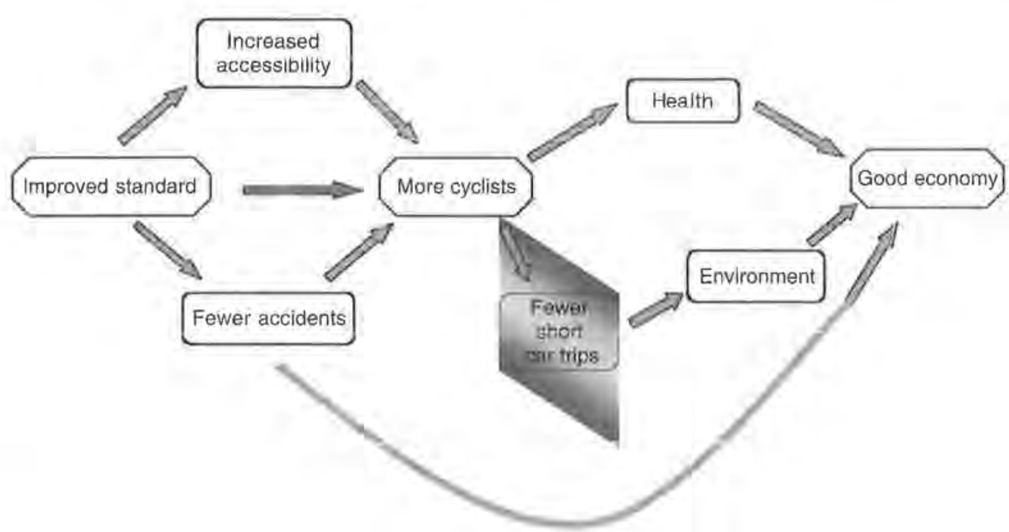

FIGURE 1 Relationship between improved winter maintenance for cycleways and benefits to society.

FIGURE 2 Mercedes Benz UX 100 equipped with a front-mounted sweeper for snow clearance and a spinner for spreading salt, brine, or grit.

and cycleways are the Multicar and the Mercedes Benz UX 100 (Figure 2). These vehicles are fast, light, and maneuverable and can easily be equipped for various applications (*13*). This kind of equipment is presently available but not in common use. The new vehicles are rather expensive, and functioning old equipment is not exchanged simply because it is old-fashioned.

Furthermore, on some occasions, all available equipment (including farm tractors) is required to clear snow from cycleways and roadways within a reasonable time. Actually, the most common vehicles used for clearing snow from cycleways today are tractors such as the Volvo BM 650 or bucket chargers such as the Lundberg 341 (*12*). In some larger communities, the smaller, newer vehicles are used more frequently. However, the old, heavy vehicles are still in use, and it probably will be decades before the entire fleet is replaced with vehicles better adapted to cycleways.

Skid Control

Skid control on cycleways in Sweden is normally done through mechanical methods that involve the application of sand, grit, or abrasive (crushed stone aggregate). Sand needs to be heated or mixed with salt to prevent freezing and thus is replaced with grit or abrasive, usually of 2- to 5-mm fraction. Abrasive, like grit, increases friction even when covered by a thin layer of snow but has little effect on black ice. The coarse material also causes punctures in bicycle tires, injures dog paws, and creates a safety hazard in spring until it is swept up. Grit may impose an environmental burden; during a thaw, grit may end up in the street sewers, where it can cause blockages. Grit also is a natural resource (quantities of which are not unlimited), and the production and transport of abrasive consumes energy.

The most common chemical method for deicing is the application of salt, usually sodium chloride (NaCl). Salt is often applied to roads used by motor traffic but rarely on cycleways. Most municipalities in Sweden stopped using salt on footways and cycleways after receiving complaints from cyclists about rust on cycle chains and from pedestrians whose clothes and shoes had been stained. Salt contaminates the environment (Blomqvist and Thunqvist in papers in this proceedings, pp. 179–194) and causes rust and concrete damage, but it is economical and readily available.

Salt can be spread dry, prewetted, or as brine. Brine is a saturated salt solution that contains about 20 to 25 percent NaCl by weight (therefore using only about one-quarter the amount of dry salt over the same area). Brine application on roads decreases the salt concentration considerably and is preferred for cycleways because cycling traffic is too light for dry salt to work effectively. However, brine application is unsuitable during snowfall, on wet roads, or when ice has already formed.

Brine application is extremely effective as a preventive measure (anti-icing) and for dealing with hoarfrost (which is caused by a combination of temperatures below 0°C and high moisture content at the level of the pavement).

In fact, in Odense, Denmark, brine has been used to anti-ice cycleways since 1986 (*14*). It began as an experiment on a few stretches but produced such good results that brine alone is used for skid control on cycleways in Odense today.

Evaluation Methods

To establish a cost-effective maintenance performance standard and analyze the consequences of different standards of maintenance, it is important to know the snow and ice conditions on the roads. Methods of evaluating road standards are needed to compare maintenance methods for cycleways.

To determine the road conditions during the winter, visual inspection is almost the only suitable method, although it entails considerable manual effort and is subjective. The instructions available are mainly for observing roadways, not cycleways; however, the same instructions can and have been used. The work in this project has revealed the need to modify the instructions to some extent to better describe the road conditions on cycleways. The instructions for observing road conditions normally used in Sweden are described below [from Möller and Öberg (*15*) with some complementary comments by Gabestad (*16*)].

The visual inspections can be supplemented with mechanical methods such as friction measurement. However, the mechanical methods available for judging road condition often involve the use of large vehicles, which can cause overloading damage on paths and cycleways.

Instructions for Observing Road Conditions

Every observation area is 100 m long. The road surface in the observation area is surveyed and first generally categorized as one of four conditions (Level 1). Then, the general condition is given a more detailed description (Level 2). The logical construction of the road condition classification is presented in Figure 3; see Figure 4 for the survey form that is used (the form has been modified to better describe the condition on cycleways).

Level 1

Level 1 describes four basic surface conditions:

1. Bare surface. At least three-quarters of the roadway is bare. A bare surface is identical to the pavement surface condition in summer.
2. Ice and snow. At least three-quarters of the roadway is covered with ice, snow, hoarfrost, or slush from a continuing or earlier snowfall. The condition may also stem from supercooled rain or moisture that creates ice.

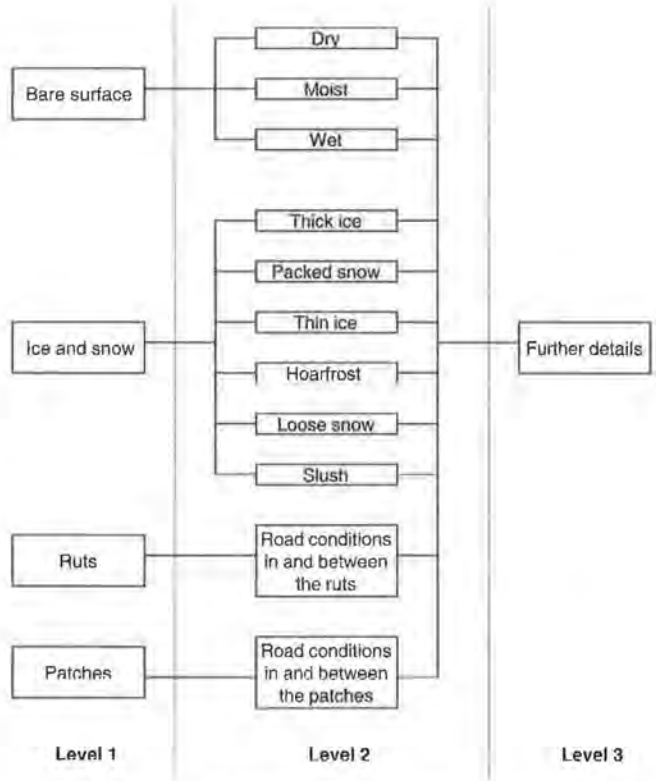

FIGURE 3 Logical construction of road surface condition classification, whereby every detailed condition is connected to a more general condition.

3. Ruts. The roadway is covered with ice, snow, hoarfrost, or slush, and wheels have worn the ice or snow layer so that the pavement is clearly visible in the ruts. Ice and snow exist between the ruts. In other words, different conditions occur across the roadway. (If the pavement is not visible, the condition is defined as "ice and snow.")
4. Patches. The roadway has ice and snow as well as bare pavement. If at least three-quarters of the roadway is one road condition, then that condition is considered to be the prevailing one.

Level 2

Level 2 describes the road conditions in more detail:

1. Bare surface. Is the surface dry, moist, or wet? If puddles of water are visible or windshield wipers are needed when following another car, even in absence of precipitation, then the road surface is considered to be wet. Otherwise, it is moist or dry.
2. Ice and snow. Descriptions include thick ice, thin ice, packed snow, loose snow, slush, and hoarfrost. The difference between thick and thin ice is its transparency; pavement is visible through thin ice but not through thick ice. A surface of thick ice may be broken only with an axe

LOCATION:.. OBSERVER:..

				DETAILED ROAD CONDITION									OCCURRENCE OF					WEATHER								TEMP.		FURTHER INFORMATION
				Bare surface									Cycle-tracks			Sand		Snowfall			Rain							
Stretch no.	Date	Time	GENERAL ROAD CONDITION	Dry	Moist	Wet	Thick ice	Packed snow	Thin ice	Hoarfrost	Loose snow (cm)	Slush (cm)	Number	Width (cm)	Irregularities	High friction	Low friction	Light	Medium	Heavy	Light	Medium	Heavy	Super-cooled	Fog	Air	Road surface	E.g. strong winds, varying road conditions, maintenance methods used, icy tracks.
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29

FIGURE 4 Protocol for describing the road surface condition on cycleways survey.

or other such implement. Packed snow is distinguished from thick ice by its white color. Loose snow may be scraped from the pavement by one's fingers, whereas the surface of packed snow is hard and cannot be scraped off without the use of a tool. Slush contains more water than loose snow and does not compact but remains soft on the road surface. If slush or loose snow is present, its depth shall be determined. Hoarfrost occurs on the pavement and usually is white.

3. Ruts. The two conditions are "in the ruts" (where the only possible conditions are bare ground and thin ice) and "between the ruts."

4. Patches. The two conditions are "in the patches" and "between the patches."

Level 3

Level 3 gives more information about the road conditions, such as the presence of irregularities, sand, and grading tracks. Irregularities appear as potholes or waves in a surface of thick ice or packed snow. Sand is considered to be present if the friction level is increased. Thick ice or packed snow is required for grading tracks to occur. Other relevant information such as weather conditions and road temperature also should be observed.

Adjustments Needed for Describing Cycleway Conditions

As mentioned earlier, the instructions for observing road conditions are created mainly for roadways, not cycleways. Not all parameters included in the method for roadways are relevant for cycleways. Other parameters are of greater importance for cyclists than for motorists and therefore should be highlighted and described in more detail when observing cycleways. Although there is no need to differentiate between roadways and cycleways when describing the general condition (Level 1), it is advantageous to shorten the observation area from 100 m to 50 m.

Ruts, a common condition on roadways—especially in countries that allow the use of studded tires—are not as common on cycleways. However, where cycling traffic is high, ruts often appear 1 or 2 days after a snowfall. They develop when many cyclists choose the same track when traveling on the cycleway. If the cycling frequency is high in both directions, the cyclists are more or less forced to choose the same track. At first the rut is just a few centimeters, but it can grow to about 40 cm, depending on temperature, the amount of snow, and the cycling frequency. Ruts represent a potential danger for passing maneuvers and are a larger hindrance for cyclists than for motorists. It is therefore important to note this condition. Even when the pavement is not yet visible in the tracks (which technically is the definition of "rut"), the number of tracks as well as their width should be determined. In such a case, the general road condition would be "snow and ice," and the tracks would be presented only in the detailed description (Figure 4).

Detecting other kinds of tracks is also important and should be described in the detailed description of road conditions. Icy tracks are often formed on cycleways when wet snow freezes. Interviews and comments in a questionnaire survey performed early in this project indicated that these kinds of tracks are what cyclists fear most. Icy tracks are considered to be both troublesome and dangerous.

Other detailed information important for cycleways includes the occurrence and amount of grit on the surface. In the instructions for observing roadways described earlier, the occurrence of grit was to be noted when it was judged to increase the road surface friction. However, for cycleways, it is important to distinguish whether grit increases or decreases friction. If the amount of grit is more than needed, the friction level on the surface is decreased rather than increased, which is the fundamental purpose of grit application. (Such is often the case during mild winters, when the general road condition is often bare ground.) On roadways, friction level is almost never decreased, because air turbulence from motor traffic quickly transports the grit off the road surface.

Measurement of Coefficient of Friction

Surface friction is one of the most important features concerning road conditions. It is particularly important during winter, because snow and ice on the road surface decrease friction considerably. When the friction level on the pavement surface is lower than what may be considered safe, the surface is considered to be slippery or seriously slippery. In Operation 96 of the Swedish National Road Administration's General Technical Description of Operation Service Levels (*17*), a surface with a coefficient of friction below 0.25 is considered "slippery" (Table 1).

The friction coefficient can be measured with several methods and devices. One method normally used to measure friction on roadways in Sweden is the Saab Friction

TABLE 1 Friction Coefficients Defining the Road Conditions in Terms of Slipperiness, According to Operation 96 (*17*)

Class	Friction coefficient
Satisfactory friction	$\mu \geq 0.25$
Slippery	$\mu < 0.25$
Seriously slippery	$\mu \leq 0.15$

NOTE: The friction coefficient is defined as the average value over a 20-m stretch, as measured with a Saab Friction Tester or analogous equipment.

Tester. This device uses the wheel-slip principle, whereby a slipping wheel is installed in a car (a Saab), enabling a continuous measurement of friction at a moderate highway speed. Table 2 presents friction coefficients representative of different road conditions measured with the Saab Friction Tester. As Tables 1 and 2 show, a roadway free of snow and ice is always considered to have satisfactory friction, whereas the presence of ice almost always creates a slippery or seriously slippery condition. Packed or loose snow provides a friction level that can be either satisfactory or slippery.

The Saab Friction Tester can be used on cycleways as well as on roadways. However, because of limited space and for the safety of cyclists when performing the measurements, other devices are preferable. A portable instrument for measuring friction over short distances (down to 1 m) has been developed at the Swedish National Road and Transport Research Institute (*19*). The Portable Friction Tester (PFT; Figure 5) is a three-wheeled hand-pushed cart of which one of the wheels has a variable slip. Friction is measured in terms of the force on this wheel, sampled with variable frequency. This equipment was originally designed to measure friction on road markings in wet conditions, but it also can be used on cycleways.

The PFT has not been scientifically compared with the Saab Friction Tester. However, it has been compared with the British pendulum (*19*); it is possible to predict friction values measured by the PFT into British pendulum units. Thus the PFT has high validity, if it is assumed that the pendulum shows the "true" friction. Furthermore, the repeatability of the PFT measurement has been good and the measurement less time-consuming than with the pendulum.

FIELD STUDIES

Purpose

The main purpose of the field study was to test an unconventional method for snow clearance and deicing of cycleways. The field study surveyed, through questionnaires, the users' opinions of the tested maintenance method compared with traditional methods with respect to degree of snow clearance, surface friction, and so forth.

To compare different road conditions, an evaluation method for cycleways was needed. Therefore, another purpose of the field study was to develop a method for describing road conditions on cycleways.

TABLE 2 Friction Coefficients Representative of Different Winter Road Conditions Obtained with a Saab Friction Tester (*18*)

Road condition	Friction coefficient
Dry bare ground	0.8–1.0
Wet bare ground	0.7–0.8
Packed snow	0.2–0.3
Loose snow/slush	0.2–0.5
Thin ice	0.15–0.30
Loose snow on thin ice	0.15–0.25
Wet thin ice	0.05–0.10

NOTE: For loose snow or slush, the higher values represent the occasion when the slipping wheel is in contact with the pavement.

FIGURE 5 Portable friction tester, constructed at the Swedish National Road and Transport Research Institute for measuring the friction over short distances.

Methods

Instructions for observing road conditions on roadways, found through literature reviews, were developed to better describe cycleway conditions (described under Evaluation Methods.) A preliminary study was conducted to obtain information for an extensive study on how to improve the instructions for observing road conditions on cycleways and the problems that certain maintenance methods could expect.

Two frequently used cycling paths in Linköping were chosen for the study, which was carried out in February and March 1999. Observations of the road surface conditions on the cycling paths were conducted after each snowfall or hoarfrost. On two occasions, in addition to the observations, friction was measured with a PFT, which was considered practical in this case because it was difficult to use other measuring devices. To obtain an idea of the cyclists' opinion of the condition of the cycling paths included in the study, roadside interviews were carried out on four occasions.

Two different and unconventional methods of snow clearance and skid control were tested on the selected cycling paths in the pilot study. The front-mounted sweeper for snow clearance combined with a brine spreader for deicing (Figure 2) showed good results and therefore was used in the large-scale study the following winter. The snow sweeper was meant to reduce any remaining layer of ice and snow so that the salt dosage needed to achieve an acceptable standard could be minimized.

The large-scale winter study was carried out between October 1999 and March 2000. In this study, part of the network of cycleways in Linköping was used as a test area. In the test area, cycleways received a higher level of service than usual; the front-mounted sweeper and brine (for deicing) were used to achieve the higher standard. Snow was cleared and skid control applied more frequently than on other cycleways. Snow clearance was begun at a depth of 1 cm of loose snow, and deicing at every occasion of ice, snow, or hoarfrost. (In Linköping, snow clearance is usually started at a depth of 3 cm, using a traditional steel plow and abrasive for skid control.)

The large-scale study was evaluated in much the same way as the pilot study. Throughout the winter, observations of the road conditions on cycleways in the test area and on reference stretches were carried out whenever necessary, at least after every snowfall. Interviews and measurements of friction were conducted on a few occasions. The large-scale study will be evaluated through an extensive survey of users' opinions of the new methods. A total of 850 questionnaires have been sent out to inhabitants in the test area and to reference groups.

Results

Because the pilot study was completed quickly, its results were limited. However, the maintenance method using a sweeper for snow clearance and brine for deicing gave such good results that it was considered interesting to study further. Friction measurements showed that the friction level on the cycling paths where this method had been used was considerably higher than on reference paths (Figure 6). At the time of measurement, the cycling path included in the test was wet and bare, whereas the reference path was covered with snow. It is not surprising that the snowy surface is more slippery than the bare ground. Nevertheless, it shows that the test method resulted in a surface less slippery than did the maintenance methods normally used.

The instructions for observing road surface conditions on cycleways proved to be adequate for the purpose. Only a few adjustments in the protocol for the inspections were needed (described under Evaluation Methods). However, visual inspections needed to be done more frequently than during the pilot study.

The roadside interviews conducted during the pilot study indicated that cyclists' opinions were more positive than expected toward the use of brine in eliminating ice on cycleways. Of the 122 persons interviewed on five different occasions, a majority (53 percent) thought it was acceptable to use brine on cycleways. Only 30 percent were against its use, and the remainder were unsure.

The large-scale study has not yet been fully evaluated. However, observations of road surface conditions showed that the ground in the test area was almost always bare and dry, moist, or wet throughout the winter, no matter what the conditions were on other cycleways in the municipality. These observations imply that the test method provides a better level of service than methods traditionally used in Linköping. However, winter was unusually mild during the test period, which means that the results may not apply to all kinds of winter conditions in this region. Also, in a few stretches in the test area, the pavement was in such bad condition that it was difficult to clear the snow completely.

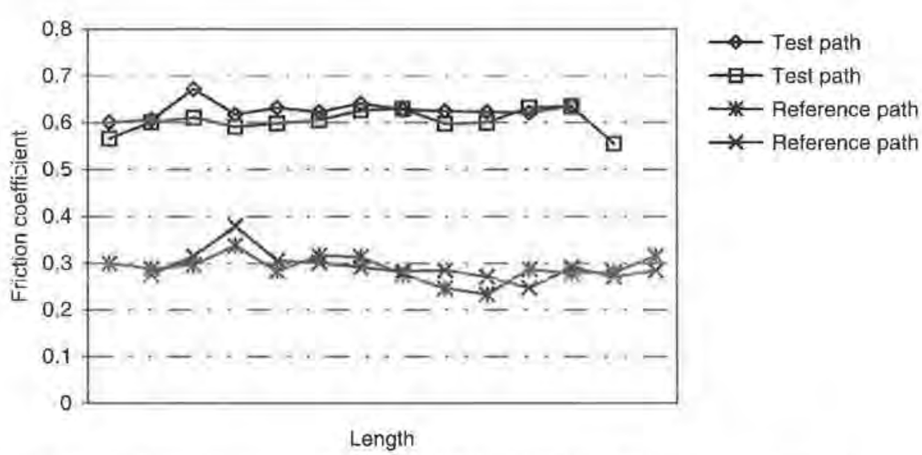

FIGURE 6 Measurements of friction performed in the pilot study conducted in Linköping.

Conclusions and Additional Studies

Winter maintenance methods for cycleways are often adapted from those for roadways, and as such, they are not necessarily the best methods for cycleways. However, equipment and methods are available today that are better adapted to cycleways. Because the surface condition is very important for the safety and accessibility of cyclists, it is important that appropriate methods be widely used. It is also important to improve the methods available to better suit their purposes and also to become more cost-effective. A combination of different methods adjusted to weather and road conditions is likely to be the best solution.

The front-mounted sweeper for snow clearance combined with brine for deicing is probably a good method for regions with low snow accumulations and major ice problems. Linköping and many other municipalities in southern Sweden have winter conditions of this kind. Also, in regions with colder climates, such as in northern Sweden, this method is probably advantageous during spring and fall, when the temperatures are higher and the amount of snow is less; during winter, however, other methods probably are better suited.

The use of salt always should be as moderate as possible because of its adverse effects on the environment. However, its advantages and drawbacks have to be compared with alternate methods, such as the use of abrasives. On some occasions, salt can be more cost-effective despite its environmental effects. Additional studies comparing abrasives and salt with respect to environmental effects, traffic safety, and total cost are necessary to make the right decisions about the winter maintenance of cycleways and footways.

It is also important to consider the needs of the road users. If we want people to use their bicycles whenever possible, they must have safe and trafficable cycleways. Additional studies to clearly define a good road standard from a cyclist's point of view are needed. Such methods could include, for example, surveys or bicycle counts at several occasions under varied road conditions. When the parameters important to cyclists have been identified, methods for evaluating winter road standards on cycleways can be improved even more. When striving for good winter maintenance standards, the structural standards of the pavement should not be overlooked. Potholes and other irregularities that create an uneven surface can prevent adequate snow clearance.

The PFT seems to be a good instrument for measuring friction on cycleways, especially for comparing measurements. However, additional evaluation of the instrument is needed to be able to define the road conditions more specifically based on the PFT measurements. For example, a comparison study with the Saab Friction Tester would be valuable.

Acknowledgments

This paper is part of the Ph.D. project "Effects on Cycling of Road Maintenance and Operation." The main purpose of the project is to evaluate the possibility of increasing the number of cyclists during winter by improving the operation service level on cycleways. The project started in August 1997 and is planned to result in a doctoral thesis in 2001. The project is being carried out in the Department of Infrastructure and Planning, Division of Highway Engineering, Royal Institute of Technology, Sweden. However, most of the practical work is being performed at the Swedish National Road and Transport Research Institute.

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Performance Measures for Snow- and Ice-Control Activities

Enrico V. Baroga

In 1996, the Washington State Department of Transportation implemented a system of performance measures and service levels for highway maintenance activities known as the Maintenance Accountability Process (MAP). Initially, the MAP did not include service levels for snow- and ice-control activities based on field measurement, as it does for the majority of other maintenance activities. To gain similar benefits for snow- and ice-control activities, a pilot project that included performance measures, service levels, and field measurement protocols was developed and implemented. Two performance measures were used: the amount of roadway traction provided at the time of a field measurement, and the time taken to regain bare pavement after the end of a snowfall event. More than 100 3-km (2-mi) segments of highway were randomly selected for field condition measurement throughout the winter season (November 1 to March 31). At the end of the season, point values were added together for service level determinations. The initial pilot project was assessed in spring 2000 to make revisions and to determine the long-term direction of the activity. The intended outcome of the pilot project is to identify a performance-based service level being delivered for snow and ice control. This information could then be used for more accurate budget planning and resource allocation in the future.

In developing performance measures for snow- and ice-control activities, the Washington State Department of Transportation (WSDOT) faced some significant challenges. One of the greatest challenges is the diverse geography and climate in Washington State. This kind of diversity may not have a significant bearing for measuring something such as guardrail maintenance, but it is integral in measuring performance for snow- and ice-control activities.

Washington is a fairly mountainous state. The Olympic Mountains lie in the western portion; the Cascade Mountains run from Canada to Oregon down the middle; and several lesser mountains are found in the eastern half of the state. Being located on the receiving end of moisture-laden weather systems coming directly off the Pacific Ocean, many areas in Washington receive copious amounts of precipitation. The combination of precipitation and mountainous terrain results in significant amounts of snowfall. Washington State holds the world record for snowfall during a single winter season, set during winter 1998–1999 at Mount Baker, where total snowfall was 2896 cm (1,140 in.). The world record before this was also in Washington: 2851 cm (1,122.5 in.) at Mount Rainier. Throughout the winter, WSDOT maintains and operates 10 mountain-pass highways, where it must deal with large volumes of snow. A performance measure for maintenance activities on mountain-pass highways logically should address snow removal.

A large part of western Washington (coastal lowlands) includes the vast majority of the state's population centers (e.g., Seattle) and highway traffic. These areas experience a fairly mild maritime climate with large amounts of rainfall but not too much snowfall—maybe one or two minor snow events per winter. In some years, the coastal lowlands have no snow at all. However, during occasional

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cold spells, frost events are common, so most of the snow and ice control in these areas consists of pretreating with anti-icing chemicals and spreading sand on icy highways for traction. Obviously, this focus is considerably different from that in the mountain passes, and the same performance measure will not work for both areas.

The other large geographic area is the inland plateau on the east side of the Cascade Mountains. This area does not get the large amounts of moisture from the Pacific Ocean or a moderating effect on its air temperatures. The climate is dry and cold; winter is characterized by numerous frost events and moderate snowfall. Most efforts from maintenance forces during the winter are managing icy roads, by pretreating with anti-icing chemicals or applying sand for traction. It is not unusual to have subfreezing temperatures on 80 percent of the days during the winter season (November 1 to March 31). A performance measure that works well for mountain-pass highways or coastal lowland areas may not be in the best interests of eastern Washington.

In addition to the challenges in measuring snow- and ice-control performance related to Washington's geographic diversity, the dynamic road conditions found during winter weather events further complicate performance measurement. One hour, the roadway can be icy and dangerous; the next hour, it can be bare and wet without any intervention from maintenance personnel. When and how performance is measured in such an instance can make a world of difference.

Sometimes when a problem is being addressed, a single solution is obviously the one and only answer to the question. No such solution was found for snow and ice control. Performance can be measured in several ways, none of which is absolutely superior to all others under all circumstances. WSDOT sought a solution from its counterparts around the United States but was unable to find another state department of transportation (DOT) that had a time-tested model to follow that would suit its needs. Some DOTs were measuring snow- and ice-control performance (such as the California and Minnesota DOTs), but they, too, were in fairly early stages of developing their measures and learning from experience.

Performance Measures

A team of maintenance personnel was assembled to develop snow- and ice-control performance measures and the associated data collection protocols. The team was primarily made up of regional maintenance personnel who had considerable experience with snow- and ice-control activities.

Two performance measures that were to be combined into a single level of service (LOS) rating for snow and ice control were developed. The first measure was a rated condition of a representative segment of highway at a given time during each week of the winter season. Specifically, the roadway segment would be rated based on the extent to which it was maintained in a bare (bare and dry, or bare and wet) or sanded condition. The highest score (1 point) would be assigned to a surveyed segment of highway that was either completely bare or completely sanded. As the extent to which the survey segment was maintained in a bare or sanded condition varied, other point values (2, 3, 4, and 5 points) were assigned. The conditions were distinguished primarily by identifying "emphasis areas" (e.g., curves, hills, and intersections) that were maintained in a bare or sanded condition. Although this performance measure gave an indication of the condition to which the roadway was maintained throughout the winter, it did not really indicate how well WSDOT responded to individual storm events—an important part of its task, especially in the eyes of its customers.

Thus, a second measure was added that focused on the time to regain bare pavement after a winter precipitation event ends—that is, the hours elapsed between these two points. Point values (1 through 5, where 1 is the highest and 5 the lowest) were assigned to different hour thresholds; faster times resulted in higher scores and slower times in lower scores. Different hour thresholds were assigned to different categories of highways. For example, a category 1 highway [average daily traffic (ADT) > 80,000 vehicles] would be assigned a high rating of 1 point if bare pavement conditions were maintained during the winter precipitation event. However, a category 5 highway (ADT < 5,000 vehicles) would be assigned the same high rating if bare pavement could be regained within 6 h of the end of the winter precipitation event.

The second performance measure was used only when a winter precipitation event was occurring at the time of the field survey. The point values of the two performance measures were translated into a letter grade (A, B, C, D, or F) LOS rating similar to those of other Maintenance Accountability Process (MAP) activities.

Who, When, Where, and How

Quite a few more details pull together the two performance measures into a full-fledged pilot project. Field surveys were assigned to regional maintenance personnel throughout the state. Training sessions were conducted in the 24 maintenance areas at the beginning of the winter season to ensure adequate communication about and understanding of the performance measure procedures. Personnel from WSDOT's central maintenance office also conducted field surveys on a small percentage of the highway segments that were surveyed by regional maintenance personnel for quality assurance and quality control (QA/QC) purposes.

For the purposes of performance measurement, the winter season was defined as the period between November 1 and March 31. All the field surveys were conducted during this time.

For the first performance measure (rating the condition of the roadway), one field survey was conducted at each survey point every week of the winter season. The weekly field checks were conducted on designated days; different maintenance areas were assigned different days, Monday through Thursday. All field checks were conducted between 6 a.m. and 9 a.m. statewide for consistency.

A total of 133 3-km (2-mi) highway segments around the state were randomly selected to be assessed for snow- and ice-control performance. The sites represented various categories of highways based on ADT. At survey locations, the focus was on the condition of the mainline highway between the foglines. All lanes of travel within the survey segment were included—lanes in both directions on divided as well as undivided highways. If conditions varied across multiple lanes, the surveyor "averaged" the conditions and recorded the data. Roadway shoulders, pull-outs, chain-up areas, and other areas outside the main travel lane were not included for the purposes of the pilot project, nor were on-ramps, off-ramps, and overpasses.

The performance assessments were conducted via a "windshield survey." Whereas other MAP field survey protocols (such as those for pavement patching and repair) require maintenance personnel to leave their vehicles, walk the roadway, and take some fairly precise measurements, the performance measures for snow and ice could be obtained from the safety of their vehicles.

The information from each field survey was documented on a one-page form (Figure 1). Some people preferred to use electronic forms, whereas others used paper forms; both options were available. In some areas, radio dispatchers completed forms at the office from information transmitted via radio from personnel in the field.

The LOS ratings from the pilot project were to be accompanied by an index value that reflected the severity of winter in Washington State. This value would help provide the appropriate context (a severe winter or a mild winter?) within which the LOS rating could be used. The index was based on the winter index (WI) developed by the Strategic Highway Research Program (SHRP H-350).

The WI (Figure 2) includes snowfall data in its calculation. WSDOT wanted to have a "real-time" WI for use during the winter season, but real-time snowfall data are not available statewide in Washington. So, the WI was modified by removing the snowfall data and renaming it the "frost index." Frost indices were calculated back to 1991 and compared with the winter indices for the same years. The correlation between the two indices was good, and WSDOT opted to use the frost index.

RESULTS

Analysis of the data and observations of the pilot project's participants yielded mixed results. The data from the field data collection forms were compiled and tabulated for review and analysis. Debriefing sessions were conducted in each of the 24 maintenance areas to gather observations and input from the regional maintenance personnel who were involved with the pilot project.

The tabulated data (Figure 3) show an overall level of service to be slightly higher than average. No data were used in the tabulation unless it was the result of specific maintenance activities. In other words, all of the "bare pavement" ratings that received this rating simply due to warm weather conditions were thrown out. Only ratings for bare pavement that were the result of anti-icing chemical application and ratings for sanded pavement were used.

Without the benefit of field measurements, the LOS provided has been traditionally estimated to be in the C-to-C+ range (average), whereby motorists are likely to experience some delay and slow travel on roads with black ice, packed snow, or only portions of the roadway sanded or treated with anti-icing chemicals. The data from the pilot project produced a statewide overall LOS of B+. Many maintenance managers at WSDOT felt that a B+ was a higher LOS than was actually provided.

Integration of two factors can help clarify the significance of the B+ LOS. Throughout all of western Washington and most of eastern Washington, the winter of 1999–2000 was considerably warmer than average. Approximately three-quarters of the weekly field surveys statewide resulted in a "bare pavement" rating simply because the weather was above freezing. Additionally, mountain-pass highways (category 6) were not included in the body of highways from which the survey locations were randomly selected. Because winter conditions vary so much more in mountain-pass areas than at lower elevations, these highways were excluded in the initial pilot project. If the winter had been more severe and mountain-pass highways had been included for field surveys, one could reasonably expect that the overall LOS would have been lower than the B+ attained—probably much closer to the C or C+.

The LOS calculated for individual regions was higher in western Washington than for those in eastern Washington. Because of the few subfreezing weather events in western Washington, the higher LOS for the western Washington regions appears to be more related to the mild weather than the LOS actually provided by the maintenance program.

In general terms, the performance measures and data collection protocols seemed to work out fairly well for field personnel. The personnel who conducted the field surveys indicated that the measures and protocols were

Site No: [ ] SR No: [ ] Beg MP: [ ] End MP: [ ]

Category No: [ ] Sample Date: [ ] Sample Time: [ ]

Name: [ ]

Part 1 - Traction Control **Sample Time Range: 6:00 am to 9:00 am weekly**

Sanding:
Condition Indicator: Presence of sand on 60% or more of the traveled lane. Emphasis areas are defined in the Maintenance Manual to include bridges, hills, curves and intersections.

Outcome Measurement: Percent (%) of traveled way sanded.

- [ ] Bare
- [ ] Entire Sample Area Sanded
- [ ] Emphasis Areas & 50% or More of Remaining Area
- [ ] Emphasis Areas Only
- [ ] 50% or More of Emphasis Areas
- [ ] < 50% of Emphasis Areas

Part 2 - Precipitation Event **Precipitation At 35 Degress or Below**

Begin Date: [ ] Begin Time: [ ] Precipitation End Time: [ ]

End Date: [ ] Time When Bare Pavement Achieved: [ ]

Elapsed Time (Hours): [ ]

Event Type: [ ] Snow [ ] Freezing Fog [ ] Freezing Rain [ ] Other [ ]

Traveled Way Condition (Fog Line to Fog Line):
Condition Indicator: Presence of bare pavement.
End of Event Indicator: A cessation of precipitation for a 6 hour period.
Outcome Measurement: Elapsed time from the end of precipitation to attainment of bare pavement.

[ ] Part 2 Invalid

Elapsed Time To Bare Pavement:

Category 1	**Category 2**	**Category 3**	**Category 4**	**Category 5**
[ ] Bare Pavt Maint	[ ] Bare Pavt Maint	[ ] < 2 Hours	[ ] < 4 Hours	[ ] < 6 Hours
[ ] < 2 Hours	[ ] < 2 Hours	[ ] < 4 Hours	[ ] < 6 Hours	[ ] < 8 Hours
[ ] < 4 Hours	[ ] < 4 Hours	[ ] < 8 Hours	[ ] < 12 Hours	[ ] < 16 Hours
[ ] < 6 Hours	[ ] < 8 Hours	[ ] < 12 Hours	[ ] < 16 Hours	[ ] < 24 Hours
[ ] > 6 Hours	[ ] > 8 Hours	[ ] > 12 Hours	[ ] > 16 Hours	[ ] > 24 Hours

Comments:(weather conditions, presence of deicer or anti-icing materials, other)

FIGURE 1 Field data collection form.

clear and understandable and that they could be applied and interpreted consistently around the state. Preliminary feedback indicates that the system was not much of a burden. Regional personnel did not report that they were spending so much time conducting field checks that they could not do their regular jobs. After having completed the winter pilot project, maintenance personnel felt that WSDOT was measuring the right things to represent the LOS it provided.

Regional maintenance personnel indicated that some of the surveys that resulted in a "bare pavement" rating were not included in the overall LOS calculation because sometimes people did not indicate the bare pavement condition due to pretreatment with anti-icing chemicals.

$$WI = -25.58\sqrt{TI} + (-35.68)\ln((S/10)+1) + (-99.5)\sqrt{N/(R+10)} + 50 \; *$$

Temperature Index (TI) = 0 if the minimum air temperature is above 32°F; 1 if the maximum air temperature is above 32°F while the minimum air temperature is at or below 32°F; 2 if the maximum air temperature is at or below 32°F. The averaged daily value is used. (Weighted 35%)

Snowfall (S) = the daily amount of snowfall in millimeters. (Weighted 35%)

Number of Air Frosts (N) = mean daily values of days with minimum air temperature at or below 32°F. (Weighted 30%)

Temperature Range (R) = the difference between the mean monthly maximum air temperature and the mean monthly minimum air temperature. (Weighted 30%)

* The four coefficients in this equation tailor the Winter Index to United States climate.

FIGURE 2 Winter index calculation.

Leaving this information as something to be added in a general comments box on the form rather than including it as a formal check box was the main reason these records were lost.

The North Central Region opted to include additional survey sites so they could have ratings more representative of the LOS provided by their individual maintenance areas. At the end of the winter season, one maintenance area that had aggressively used anti-icing chemicals had a lower LOS rating than an adjacent maintenance area that had relied more on conventional plowing and sanding practices, with limited use of anti-icing chemicals. Observations and experience (as well as input from the traveling public) indicated that these LOS ratings did not accurately reflect the snow- and ice-control services that were actually provided by one area relative to the other.

To understand the cause of this problem, WSDOT examined the individual field condition surveys from the two subject maintenance areas and found discrepancies in the way Part 2 of the form was being completed. The system was designed so that Part 2 would only be completed if a winter precipitation event was occurring while the weekly field survey and Part 1 completion were taking place. However, on the majority of the forms for which Part 2 had been completed, the documented time when bare pavement was regained occurred before the field check even began. Apparently, many people had understood that if any remnant of a winter precipitation event remained on the roadway at the time of the weekly field check, then Part 2 of the form should be completed—the time to regain bare pavement from the previous event calculated and recorded. After the records were deleted that had been incorrectly completed, the LOS rating for the area that was believed to have provided a higher LOS rose above that of the adjacent area perceived to have provided a lower LOS.

After identifying this problem in 2 of the 24 maintenance areas, individual field survey records in other maintenance areas were examined. The problem was found to be fairly pervasive throughout the state. All records of incorrectly completed forms were deleted from the tabulations. Although many of the area and regional LOS ratings changed to varying degrees, the overall statewide LOS remained nearly identical.

The main revision that regional maintenance personnel wanted in the system was to have more flexibility in selecting locations and times for the field surveys so response to more subfreezing weather events could be measured. They felt some frustration in being limited to a single 3-h period during the week in which the field survey could take place. WSDOT responses to many subfreezing weather events were not measured for inclusion in the LOS rating because the events took place outside of the designated survey time or day. Also, some of the randomly selected survey sites were at locations least likely to experience severe snow or ice conditions in a general area. If those locations had been moved to where the likelihood of snow or ice conditions were more prevalent, opportunities for measuring our response to subfreezing weather events would have increased.

The weather information that supplies the data for the frost index is obtained from the National Weather Service (NWS), which gathers daily high- and low-temperature readings from a multitude of weather stations throughout the state and makes them available on their website. The data are tabulated in a format that is amenable for use in calculating the frost index.

In late summer 1999, the NWS website crashed and had to be reconstructed. As of May 2000, the component of the NWS website that contained the temperature data had not been reestablished. The NWS webmaster has stated that NWS intends to provide this information on their website in the future. WSDOT is currently exploring other options in case acquisition of the needed data continues to be problematic in the future.

CONCLUSIONS

Nothwithstanding some of the problems mentioned earlier, the WSDOT pilot project appeared to meet its objectives. Performance measures, service level ratings, and field measurement protocols for snow and ice control were developed and implemented. Although assessment of the pilot project revealed the need for improvement and revision, the basic principles in this system are sound and suitable for future incorporation into the MAP.

The team that initially developed the performance measure system for snow and ice will reconvene in the summer of 2000. They will evaluate the results of the

FY2000 STATEWIDE MAP SNOW & ICE SURVEY RESULTS

Sampling Statistics

Description	Number	Percent
Total Surveys	1,718	100.0%
Total Bare Pav't Surveys	1,441	83.9%
Total Bare Pav't Surveys w/ Deicer Use	136	7.9%
Total Non Service Level Surveys (2-3)	1,305	76.0%
Total Possible Part 1 Surveys (1-4)	413	24.0%

SL	Threshold
A	1.0 - 1.9
B	2.0 - 2.9
C	3.0 - 3.9
D	4.0 - 4.9
F	5.0

Part 1 - Traction Control

Description	Number	Percent	Multiplier	Score	Service Level
Total Bare Pav't With Deicer Use	136	33.8%	1	136	
Entire Sample Area Sanded	96	23.9%	1	96	
Emphasis Areas & 50% of Remaining	59	14.7%	2	118	
Emphasis Areas Only	41	10.2%	3	123	
50% of Emphasis Areas	25	6.2%	4	100	
< 50% of Emphasis Areas	45	11.2%	5	225	
Total Sanding Records	402	100.0%		798	**2.0**

Part 2 - Precipitation Events

Description	Number	Percent	Multiplier	Score	Service Level
Category 1 Records	0	0.0%			
Category 2 Records	8	8.3%			
Category 3 Records	17	17.7%			
Category 4 Records	19	19.8%			
Category 5 Records	52	54.2%			
Total Records All Categories	96	100.0%			
Combined Categories - box 1	61	63.5%	1	61	
Combined Categories - box 2	8	8.3%	2	16	
Combined Categories - box 3	8	8.3%	3	24	
Combined Categories - box 4	2	2.1%	4	8	
Combined Categories - box 5	17	17.7%	5	85	
Total Records All Categories	96	100.0%		194	**2.0**
Combined Part 1 & 2 Service Level					**2.0**

FIGURE 3 Tabulated pilot project data.

pilot project and make revisions as needed before continuing implementation during the winter of 2000–2001. WSDOT anticipates that increased flexibility in survey site location and time will be incorporated in an effort to increase the data available for LOS calculations. It is also anticipated that mountain-pass highways will be included, additional detail (e.g., application of anti-icing chemicals) will be added to the form, and increased QA/QC measures will be implemented to identify problems early and make adjustments as needed.

One indirect result of this pilot project is that more field maintenance personnel have been included in performance measurement than ever before. For a long time, performance measures and performance-based budgeting were something the people at headquarters dealt with. That scenario has been changing. With their participation in the snow and ice pilot project, regional maintenance personnel have learned about the tools and benefits that MAP provides to assist them in the day-to-day delivery of the highway maintenance program services.

Synergy Program in San Diego, California

Jonathan Levy and Elizabeth Mueller

The city of San Diego (California) Street Maintenance Division developed the Synergy Program to improve working methods and employee responsibilities, track performance measures, maintain inventories, and implement new technologies. As changes took place, the need for an effective and integrated inventory and work management system became critical. To develop a new system for inventory and work management, an enterprise resource planning system proposed by SAP America was chosen. The proposed system provided full inventory and work management functionality and required reengineering business practices to use the "best practices" proven by major organizations. An SAP/geographical information system (GIS) browser was developed that allowed data in the SAP system to be viewed spatially using GIS. Employees assigned to the project were assisted by implementation consultants and became the experts on the software and on business process reengineering. They were instructed to make decisions that were "directionally correct" (i.e., that kept the division moving in the right general direction) and to keep the project as simple as possible. As a result, the project went into production in record time and within budget. The implementation proceeded in three phases: scoping, initial implementation, and system expansion. The fourth phase, currently under way, is a process of adding inventories and improving the system based on observations made during the first year of operation.

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The city of San Diego Street Maintenance Division maintains all of the streets, alleys, sidewalks, street trees, storm drain systems, street lights, traffic signals, traffic signs, pavement stripes and markings, marked curbs, fences, guardrails, and bridges for a city of 1.2 million people who live in an area of 1041 km^2 (402 mi^2); the region—including the adjacent and similarly sized city of Tijuana, Mexico—is home to 4 million residents. San Diego's Street Division also provides services such as street sweeping, emergency response to hazards, and storm water pollution control management and enforcement.

From the mid-1970s to mid-1990s, the city experienced major growth without any changes in the management structures and information systems of the maintenance division. The traditional method of passing all operational information verbally from supervisor to employee and then promoting that employee was no longer feasible. What had worked for a city of 700,000 inhabitants with 2400 km (1,500 mi) of streets no longer was effective with 4800 km (3,000 mi) of streets, 18,000 intersections, and more than 1 million people. The systems could not meet current-day expectations and did not provide resources that were competitive with private service providers.

The Street Division was faced with a major challenge. The primary request-tracking system was limited and overloaded. There were more than a million separate items to maintain and 363 employees to manage, as well as their equipment and materials. Numerous maintenance contracts were in process, new technologies were being evaluated, and an annual budget of $42 million had to be developed and managed. A goal was set to complete a major new service tracking, work management, inventory management, and management information system within 1 year. To achieve this goal within budget and on schedule seemed an impossible task, especially within the constraints of working in the public sector.

Surprisingly, when the year was over, the division had done better than that. More had been accomplished than originally planned, and the project had been completed on time and on budget. In this paper, we describe the process used to implement this system, the methods used to improve the work management practices of the division, and the system itself.

Work Management and Inventory System

The division had an immediate need for an effective and economical work management system. Different sections within the division used different inventory and request-tracking systems. These systems were not compatible and varied from handwritten records with no inventory to computer files in Paradox, Quattro Pro, and mainframe systems.

The largest of these request-tracking systems had no geographical basis and no ability to measure actual work done. This system kept track of requests received and their completion but maintained no centralized record of routine work processes. The mainframe system, designed when the city had a population under 750,000, had significant problems during the heavy rains in the spring of 1998. It was unable to process the number of requests received each day for much of the spring, requiring the use of pen and paper to track many thousands of requests.

There also was a long-term need for improved management information to measure the work performed and associated costs; these measurements had been collected manually and summarized. The method led to variations in the measurements and the inability to individually audit the work done in each category. This need was not only expected by the public and the elected representatives but also a crucial comparative measure as part of a citywide "competition program" whereby services provided by city staff were bid directly against private service providers.

To determine the division's needs, a business case was drafted to define what a new system should provide and could achieve. Needs included tracking all items maintained and all work performed to allow an increase in planned maintenance in lieu of reactive maintenance; providing an improved level of service to the public by tracking customers, their requests, and the results of those requests; and especially improving work efficiency. One common complaint by field units was that their time was wasted responding to locations that did not exist, locations where the item to be repaired did not exist, locations where the work requested had already been completed, or locations where the work to be done conflicted with work planned by others. Time also was nonproductive when one crew was assigned to coordinate work with another crew. Often, one crew would attempt to start work before the other crew was ready, or the follow-up work was never completed. When work was not completed, a normally scheduled task suddenly became a high priority, displacing planned work and reducing productivity. A study of more than 6,000 requests found that 18 percent of the responses were nonproductive. Determining repeat requests, conflicting work, and the existence of specific maintenance items at a location was especially difficult to handle by conventional methods. The use of geographical information for all data was determined to be the best method to address these problems.

Another major concern to municipalities is liability. A work management system can address liability issues in two ways. The first is by aggressively tracking and coordinating all work. If the work is done properly and in a timely manner, the possibility of damage or injury leading to liability is reduced. The second method is by having a comprehensive record of all requests and routine repairs made to a street element. When presented in court, these records give the jury the knowledge of the effort and completeness of the work actually done. With the previous system, this lack of information gave the impression of incompetence and unreliability.

Five possible ways to proceed were identified:

- Upgrading one or more of the existing mainframe applications currently in use,
- Creating a unique client-server–based system,
- Modifying an existing client-server–based system under development from another city department,
- Purchasing an existing public works package, and
- Using an enterprise resource planning (ERP) system and creating a link to a geographical information system (GIS) package.

The first three options (upgrading, creating, or modifying a system) would require extensive needs analysis, design, prototyping, and programming. The most optimistic time frames for these processes were more than a year and likely would have required several years to full implementation. In addition, on completion, these systems would be static; only with additional direct expenditures of effort and money would they be able to expand to address new needs or to use the rapidly advancing improvements in communications.

On the basis of the city's immediate needs and concerns regarding the time frame and cost of developing a customized system, commercially available systems were considered. The two viable alternatives were purchasing a package designed specifically for public works organizations and purchasing and configuring an ERP system. Three vendors responded to a request for proposals: two public works–specific packages and one ERP system. The demonstration and evaluation of both public works packages raised concerns about the stability of the software and its capability to handle the number of workstations and the database size proposed. However, SAP America's ERP R/3 software demonstrated the capacity to handle a large system with the many users and the large volume of data that the city required, and it was chosen. The proposal called for only a small portion of the full enterprise system to be implemented, including the plant maintenance and service management modules.

A major factor in this decision was that the system is configured—not programmed—for a business operation. This configuration had two major positive effects. First, it forced the division to rethink its operations and to choose the best work process for the entire operation, not simply recreate the dysfunctional methods from the old systems in the new one. Second, in-house operational employees—not consultants or information technology specialists—would control the implementation process. Division staff would not only make the important process decisions but also enter this information into the system, and they would have the knowledge and ability to make needed changes even after all the outside "experts" were long gone. Because the division was already in the process of considering additional process changes, the implementation of the computer system was integrated into and became central to the overall change process.

Another part of this decision was the need to tie R/3 to a GIS so that the locations could be found, managed, and reported on spatially. The answer came from Environmental Systems Research Institute (ESRI), the city's standard GIS provider, which was in the process of developing a connection to the SAP R/3 system. ESRI made a commitment to make the system functional and was able to provide the full set of tools necessary to enter, maintain, display, analyze, and translate data simultaneously in the ERP and GIS systems.

Other benefits seen in choosing the ERP system were the ongoing support and software development done by SAP that would be available to improve and expand the system in the future. Also highly desirable were the ability to easily reconfigure the system as crews and functions were added or changed in the future, and the built-in functionality in areas such as personnel tracking and materials and project management that were already available in the system. These and other functions could be turned on in the system by the necessary configuration and would fully integrate with the work management system. The support available for SAP systems (by SAP and its numerous consultants and partners) also strengthened the city's belief that this choice would be a long-term investment that would not need replacement in the foreseeable future.

So far, these beliefs have proven correct. Recent releases will add the ability to use low-cost personal handheld units with the systems as well as give system connectability to the Internet.

Change Processes

To complete the project on schedule and within budget, certain commitments were made at the top levels and passed down to the entire staff. Most important, the best and brightest formal and informal leaders were assigned to the project: three experienced first- and second-level supervisors and one engineer were relieved of their normal duties to work on the project; their normal work was absorbed by colleagues.

The information technology staff handled the hardware and network portions of the project. The entire project team was housed in a single location on the same site as most of the operations of the division to allow easy face-to-face discussions of critical subjects as needed throughout the process. The project manager and the division head were at the same location and met informally with the team at least once a day and were available when needed.

One important part of getting the system up and running quickly was to make decisions quickly and at the lowest possible level. It was made clear to involved staff that all decisions that kept the division moving in the right general direction would be supported. We found that the few instances when decisions had to be reversed and tasks redone were far less damaging than the potential time wasted waiting for approvals. The "directionally correct" concept maintained the project's momentum.

Another critical element in getting the project completed on time was to keep the project as simple as possible. The decision was made to get the system working as soon as possible. The idea was to make it work (get the basic functionality operating), then make it right (ensure that the information and process were accurate by providing high levels of support and quick corrections at the turn-on of each phase). The third phase, make it better (develop the full functionality), came later. Needs were documented, temporary work-arounds were developed, and improvements could compete for inclusion in future phases. Sometimes, "better" meant restoring functionality lost from previous systems. However, with time, most of these needs were either replaced by a new functionality or eliminated as unnecessary. Thus, many of the requests did not have long-term utility and never had to be developed.

A strong commitment toward making the necessary operational changes was necessary to improve operations and put the system in place. The system purchased did not always replicate or support existing practices; it was chosen to force the division to improve and standardize processes. Former functionality was abandoned and operational changes were accepted in some functional areas in favor of processes that better served the entire organization. It was important to avoid demands to make everything work similar to or as simply as the former systems. The overall function of the overall organization was given first priority. Resistance to reengineering is always strong, and the availability of high-level software systems may give the impression that a simple software fix will solve the staff's concerns. To have tried to make everyone fully comfortable with the new system probably would have not only put the implementation behind schedule and over budget but also would have deviated from the original goal of improving the operation.

The project team was instructed to maintain a positive mind set. No one was ever allowed to say why something couldn't be done. Instead, they were required to identify what it would take to make it work, regardless of how impossible. Then, the feasibility of the work-around plans—many of which were extremely expensive or required a declaration by the President or such—was evaluated. The process led to a positive approach to problem solving. Although the work-arounds were seldom implemented, the team found other new methods and were excited at the prospect of solving an impossible puzzle, as opposed to being depressed from listening to what absolutely could not be done.

Concurrent with the development of the work management system, several activities affected the whole division. Ongoing training outside of the normal software user classes were developed and held for supervisors, crew leaders, and administrative and technical staff. The training centered on basic information and normal skills relating to the city's structure and form of government, administrative processes, customer service, working with and leading others, and legal requirements. Work also began on reengineering business processes. Each program in the division worked with an assigned member of the implementation team to discuss plans, needs, and issues. Numerous meetings and other forms of contact began to occur. The entire program was explained at a kick-off meeting. All employees were instructed to participate aggressively and to follow the project's progress. They were each made responsible for asking questions, participating, and understanding what was going to happen as well as responsible for the success of the project in their area; if they did not participate in the process, they would forfeit all rights to complain later.

Changes in employee responsibility led to the development of a new job description and responsibilities for the first-level supervisors. The program changed their primary work responsibilities from directing work tasks to the overall management of an operational area. A new position was created, and all of the existing field supervisors and other candidates competed for placement in the new jobs.

Restructuring also was necessary to address the additional data needs of the system, especially in direct contact with customers. A call center was developed to handle the customer contact processes that involved major changes to customer service, dispatch, and clerical functions.

IMPLEMENTATION

After the decision was made to use SAP as the work management system, a request for quotes went out to implementation consultants for the scoping analysis. The scoping defined the city's business requirements and which SAP modules were going to be implemented. Before beginning of the scoping analysis, the city's implementation team spent 1 week attending training on the Plant Maintenance module of SAP's R/3 system at a remote location. This training both provided an introduction to the software and served as a team-building exercise. The city team was prepared to participate in the scoping analysis, working directly with the consultants.

The scoping analysis was a 7-week effort that included the conversion and use of existing GIS data. The selected implementation firm, Bureau Van Dijk [now Conley, Canitano & Associates, Inc. (CCAI)], dedicated three consultants to the project. They worked with the division's team to determine the specific needs of the project and designed the implementation. CCAI then developed a project plan together with ESRI, who would be developing the inventory, or GIS, portion of the project. From this plan, deliverables were specified, and a quote and time line for the SAP implementation were developed.

With the quote in hand, the decision was made to move forward with project implementation. To have a system available to begin configuration, the city moved ahead with the infrastructure part of the project—sizing, purchasing, and installing the servers and clients; system administration; software purchases; and employee training.

The implementation process, typically done in-house with the assistance of certified consultants, would entail selecting and implementing new business practices. These decisions and the actual configuration of the system would be handled by existing operational employees who were familiar with the day-to-day needs of the operation rather than by information technology specialists. With the assistance of the consultants, this in-house team would develop and conduct the training programs and would become experts on the reengineering, the new business practices, and the software.

The time line of the project defied normal standards for government projects. The scoping took place over 7 weeks from June to August 1998. The three-phase implementation started in September. The first phase, which included service notification functions and the conversion of base GIS street layers, went into production in February 1999. The second phase, which included the conversion of two of existing Street Division GIS layers (traffic signals and street lights) and the ability to maintain those objects, went into production in May 1999. The third phase, which included work order creation and preventative maintenance, went into production in June 1999. System upgrades and improvements continue in the fourth phase, as does the establishment of inventories for the remaining street assets.

What the System Does

The system has all of the normal functions of a work management system. It tracks inventory and work performed, schedules work manually and with capacity restraints, manages projects, identifies crew productivity, captures information to be used in generating billing statements, measures efficiency, and records all requests. Reports on work pending and work completed are easily generated. In addition to the normal functionality, the system also tracks customers as discrete entities and allocates all inventory and associated work by its spatial location. It allows users to see where work is planned or was done, assign or coordinate work in an area, define work areas and assignments, and develop routings for requests and routine work.

The division can create spatial maps (rather than simply provide lists of streets) for communities that show where work has been done or is planned to be done in their neighborhood. For example, one community wanted to use low-wattage bulbs in streetlights to save energy. The division provided maps of all the streetlights in the community, and the community was able to determine which bulbs were going to be changed and thus estimate the costs of the project.

The system provides very powerful reporting and management information tools. These tools are very flexible and do not require special design or programming. Especially useful is the manager's ability to "drill-down" into information, to see overall information and then all the details. For example, when a summary of all work performed on storm drains is displayed, double clicking on a storm drain number will list all the storm drain requests by crew that did the work. The information then can be drilled-down to month of work and actual jobs done. The factors that can be selected and their order can be changed and preset for each individual manager. This functionality is especially useful when data on a certain function seem to vary from what was expected. By drilling down to lower levels to see which work group, tasks, and actual jobs were involved, the manager can understand quickly what caused the unusual results.

Of special interest is a browser that ties both SAP and the GIS data together. It allows online viewing of current requests as well as the creation and update of requests found spatially. This powerful tool provides significant information and edit capabilities to the day-to-day users with a simple, understandable interface.

The Future

The fourth phase of the project, now under way, includes enhancements in three areas. The first area is the development of an interface tool for each of the remaining Street Division inventories, which were not included in the first three phases. This effort covers not only the identification of a data collection tool for each of the inventories but also the Street Division's responsibility to collect the data and enter it into SAP.

The second area is enhancements to the existing system. Some of those enhancements include the automatic updating of inventory items through confirmation of work done, increased browser functionality for creating reports and maps, training for advanced custom report development, and an evaluation of field computing technologies to be used by working crews.

The third area is a system upgrade from version 4.0 to version 4.6. In keeping with the initial decision to choose SAP for its continuing expandability, we plan to complete the system upgrade with the assistance of the consultants so that in the future, division forces can upgrade the system independently.

Along with these development efforts, a support group will be developed that will be responsible for qualifying progress, connecting the system to others in the city who are part of the division's work flow, and providing ongoing training and product support. Some future developments might include web-enabling the system to allow customers to view their requests via the Internet and to allow forces to update work from the field.

Conclusion

The success of San Diego's Street Maintenance Division's project proved that the right combination of people, products, and strong commitment can make major changes in operations and implement a complicated software system, all in a short time frame. With many major activities happening simultaneously, it was a tribute to the dedication of all involved parties that the project not only succeeded on time and within budget but also implemented more than was originally planned.

The parties (CCAI, ESRI, and the city) all had a vested interest in the success of this project. Fortunately, the entire team was highly skilled, motivated, and dedicated as well as compatible. Part of the success was due to an early decision that all work would occur in one building. The building itself, a mostly abandoned storage building surrounded by garbage truck parking, was inexpensively brought up to just below decent working conditions. But the challenges of the building and the joint challenges seemed to create a "skunk works" atmosphere that made it clear that little could not be conquered.

Part 3

ROADSIDE MAINTENANCE

Implementing North Carolina Department of Transportation Program for Maintenance Assessment and Funding Needs

Lacy D. Love and Timothy B. Baughman

The North Carolina Department of Transportation has developed and implemented a state highway maintenance assessment program. Without a method with which to assess the maintenance condition of the total system, the department's request for increased maintenance funding was based on the previous year's expenditures and an estimate of unmet needs. The unmet needs estimate was based on the professional opinion of field managers and engineers and not on actual measured quantities. A maintenance assessment program will provide a tool for tying funding levels to actual field conditions, identify inadequately maintained roadway features, and determine the funding levels needed to achieve a specific maintenance condition. A literature review was conducted, then a program framework was devised to collect roadway feature data, summarize the data collected, evaluate and interpret the results, and present the results. Then, a plan was established to determine the roadway features to be evaluated, determine survey methodology and data collection methods, determine how the condition of the features relates to department expenditures, and calculate a realistic budget to achieve an acceptable maintenance condition. By implementing a maintenance assessment program, the North Carolina Department of Transportation is taking the first step toward shifting from a reactive "fixing" mode to a proactive prevention mode. This should lead the way to greater customer satisfaction, effective use of resources, higher quality products and services, avoidance of rework, and empowerment of local managers and supervisors.

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For many years, the North Carolina Department of Transportation (NCDOT) has conducted surveys to assess the condition of pavements and bridges in the state. With information from the pavement condition survey and the bridge condition rating program, NCDOT identifies deficiencies in these assets and develops priorities and work plans to address maintenance needs. However, there was no system in place to evaluate the condition of roadside features, such as shoulders and ditches, drainage, brush and tree control, guardrails, traffic control devices, and turf condition.

Without a methodology for evaluating these features, the annual maintenance plan was based more on historical accomplishments than on actual needs of the highway system. A valid assessment of the condition of the roadside features could not be made. Maintenance work tended to be more reactive rather than proactive. Maintenance operations priorities were not based on objective data but were subject to historical accomplishments.

History of Maintenance Funding

North Carolina's highway system consists of 125 494 km (77,978 mi) of roadway. Since 1988, the number of lane kilometers has grown by 15 percent and the vehicle kilometers traveled has jumped by more than 47 percent. However, although the system and its use continue to grow, the funds necessary to maintain the system have not kept pace, as illustrated in Figure 1.

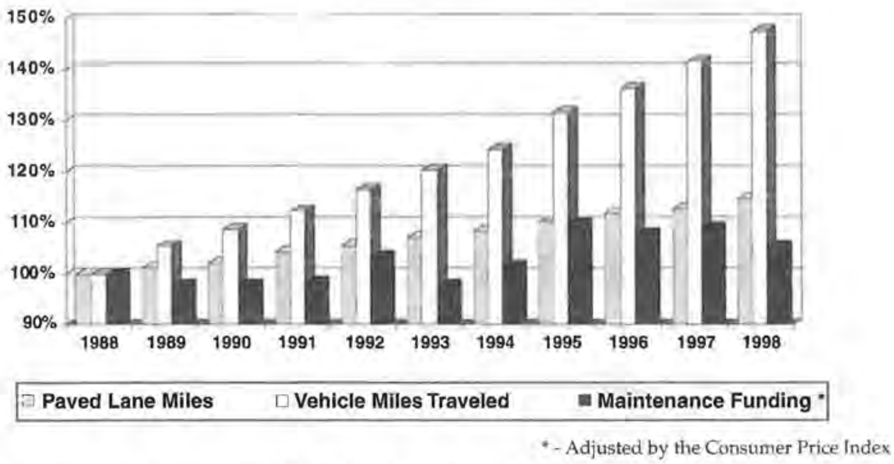


FIGURE 1 Growth of NCDOT highway system versus maintenance funding.

This growth has resulted in an increase in workload without a concurrent increase in funding. Although improving technology and more efficient operations have helped meet this greater demand, there continues to be a shortfall of maintenance funding. This shortfall has caused a backlog of work and a further deterioration in the condition of the highway system.

Obviously, insufficient funding of maintenance over time will lead to a highway system in poor condition. Previous funding increase requests have been unable to document the maintenance condition of the highway system or, if it is in poor condition, how severe the problem is. A methodology was needed to determine the condition of the state's bridge and roadway features and to estimate the cost for achieving a specific level of service.

Equally important to the determination of the system condition is the presentation of the information. The results of the maintenance assessment program must be communicated in a commonsense format that can be easily understood.

Maintenance Evaluation Strategy

In 1997, the North Carolina General Assembly passed legislation requiring NCDOT to survey the state highway system, determine the condition of the system, and develop funding needs for annual routine maintenance and the annual resurfacing program and for eliminating the maintenance backlog and the resurfacing backlog. This legislation requires the department to submit a report to the general assembly each even-numbered calendar year. The first report to the legislature was submitted in 1998, and although the next report was not due until November 2000, a second condition assessment was conducted in 1999.

NCDOT's intent goes beyond just satisfying a legislative requirement. The study also will relate funding levels to actual field conditions by providing clear links among maintenance objectives, maintenance activities, different levels of maintenance service, the maintenance budget, and actual maintenance conditions.

From this evaluation, it was expected that several objectives would be satisfied. First, the condition of the state highway system could be determined. Second, the maintenance condition is directly related to the level of funding. Third, based on the results of the survey, current funding levels were anticipated to be inadequate. Last, a strategy can be developed to calculate the amount of maintenance funding needed to achieve a predetermined level of service throughout the state.

This paper documents the procedures NCDOT used to develop a maintenance condition assessment program and how it conducted the maintenance survey program for determining the condition of roadside features. Illustrated is how this information is used, along with the pavement and bridge condition surveys, to document the overall condition of the state highway system and to estimate the cost to maintain it at an acceptable level. These results will enable NCDOT to identify features that have a low condition rating and to target funds to improve their condition. One of the goals of this effort is to shift to a proactive maintenance mode, allocating resources where needed, to provide uniform levels of service and greater customer satisfaction.

Maintenance Condition Assessment Program

As more emphasis is placed on the condition of the highway infrastructure, there is an increase in the focus of maintenance, resulting in increased workloads and greater maintenance demands. However, limited maintenance funds and even public perceptions of maintenance departments have created the need for developing quality assurance programs in the maintenance of highways. Quality assurance in highway maintenance has been described as the planned and systematic actions needed to meet the needs and expectations of the user. Building off the successes of current quality assurance programs in other states (such as Washington, Florida, and Virginia) and NCHRP Project 14-12 (*1–4*), a program was developed to implement similar management practices for NCDOT. The program is expected to accomplish the following objectives:

- Predict the funding level needed to achieve an acceptable level of maintenance;
- Relate additional funding to improved maintenance conditions;
- Develop a priority strategy to direct maintenance operations when funding levels are less than the calculated needs;
- Achieve a uniform level of service throughout the state;
- Identify areas requiring additional employee skills and equipment to accomplish tasks or the shifting of employees from one feature responsibility to another; and
- Validate that the condition of the highway system is directly related to the finding level, and demonstrate that when funding levels are inadequate, the highway system's condition will suffer.

Meeting these objectives will enable NCDOT to shift from a "fixing" reactive mode to a proactive mode of prevention, thereby incurring the benefits associated with repairs that have a lower unit cost and that do not have to be repeated. Eventually, this should lead to better-maintained highways and greater levels of customer satisfaction.

The following sections describe the method used for collecting roadway maintenance information in order to determine the overall condition of highways in the state. With these data, funding levels can be generated to address maintenance needs and a strategy can be developed for prioritizing maintenance operations.

However, a quality assessment and assurance program must be based on good data. The first step in developing a maintenance assessment survey was to identify which features would be measured and how these relate to maintenance activities.

Maintenance Activity Expenditures and Functions

Highway maintenance is those work activities associated with the maintenance and upkeep of the roadway and bridge infrastructure. Work activities can be divided into two categories: recurring programs and performance-based activities. (Although the department's effort includes all bridge and roadway maintenance work activities, for the purpose of this paper only the roadway work activities will be covered.) For NCDOT, the roadway recurring programs consist of fixed-cost programs such as incident management, rest area and welcome center maintenance, traffic signal maintenance, roadway lighting maintenance, sign lighting costs, municipal agreements, plant bed maintenance, and unpaved road maintenance. Because of the importance of these activities, allocations are largely ensured and the funding needs for these programs are very predictable.

However, expenditures for performance-based activities are more variable and depend on historical expenditures and budget constraints. These activities include routine pavement maintenance, maintenance of shoulders and ditches, drainage, mowing, litter pickup, guardrail repair, signs, pavement markings, and vegetation control. The maintenance assessment program was developed to assess these performance-based activities.

Element Features and Conditions

To ensure meaningful results, performance-based activities accounting for 80 percent of the maintenance expenditures were identified. Although it was found that ditch and shoulder maintenance activities should be a component of the assessment program, because this work accounts for nearly 11 percent of highway maintenance expenditures, there was no need to include the maintenance of pipe underdrains, which amounts to less than 0.01 percent of expenditures.

After the significant performance-based activities were identified, an analysis was made to see if they could be linked to measurable roadway features. Those that could were grouped into similar categories of elements. For example, under the element *unpaved shoulders and ditches*, a significant amount of funds was expended on rebuilding low shoulders, cutting high shoulders, cleaning ditches, and repairing ditch erosion. Therefore, it was decided that for this element, the features that the maintenance assessment survey should detect and measure were low shoulders, high shoulders, blocked ditches, and eroded ditches.

Six major maintenance elements were identified for evaluation under the maintenance assessment survey: roadway pavement, unpaved shoulders and ditches, drainage, roadside, traffic control devices, and environmental. Except for roadway pavements, each of these elements has several features and characteristics that would be evaluated against certain threshold conditions.

Following identification of the features and elements to be surveyed, the next task was to determine the threshold level at which a condition would be noted and measured. It was decided that this threshold value would be related to the point at which work ordinarily would be directed to correct the condition. For example, although a 2.5-cm (1-in.) drop-off adjacent to the pavement is a low shoulder, a maintenance crew would not be scheduled to repair the shoulder. However, a 5-cm (2-in.) drop-off would trigger corrective action and would be noted and measured. A threshold level was established for each element's feature to be identified during the maintenance assessment survey. The maintenance features and their threshold conditions are shown in Table 1. Pavements were evaluated by using NCDOT pavement rating systems already in place.

For each element feature to be surveyed, detailed descriptions of the threshold condition were developed. These are provided in Figures 2 through 6.

Conducting Survey

Because surveying the entire highway network would be an overwhelming task, a statistical sampling was made to determine the number of sites to be surveyed. With a confidence level of 95 percent and an accuracy of ±6 percent, a target sample size was calculated that would be indicative of the state's highways. Calculations were made for each of the four highway systems (Interstate, primary, urban, and secondary), and approximately 1,000 sites were randomly selected statewide for inspection, as shown in Table 2. To further expedite the survey, a team from each of NCDOT's 14 divisions was assigned the duty of collecting the field data for the primary, urban, and secondary sites. Teams from the State Pavement Management Office were given responsibility for surveying all Interstate sites.

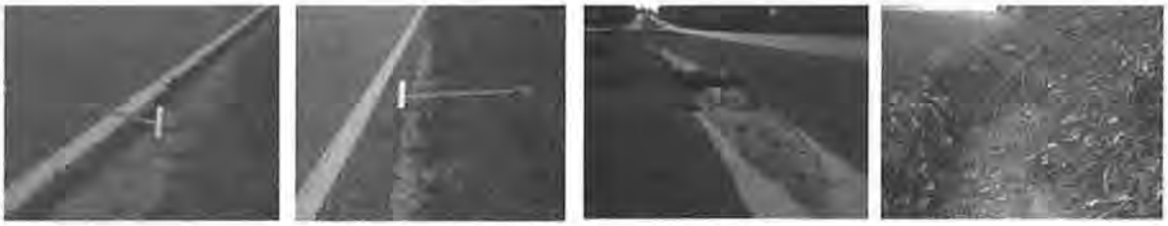
Each site consisted of a 0.3-km (0.2-mi) section. The surveys were done on foot, and the teams made several passes to adequately assess all the features. Because the information collected must be uniform and consistent, training sessions were held for the inspection teams. During training, the process and procedures were described, the elements and features were reviewed, and safety issues were discussed. Then, to ensure consistency, the teams evaluated test sections and compared their findings.

Before beginning the survey at each site, the teams marked on the pavement the beginning and ending points of the survey and the site number. Thus, the segment could

TABLE 1 Maintenance Element Features and Threshold Conditions

Element	Feature	Threshold Condition
Roadway Pavement	Flexible Pavement	*NCDOT Pavement Condition Survey*
	Rigid Pavement	*NCDOT Rigid Pavement Rating System*
Unpaved Shoulders and Ditches	Low Shoulder	Low ≥ 2 inches
	High Shoulder	High ≥ 1 inch
	Lateral Ditches	Blocked ≥ 50% and Not Functioning as designed
	Lateral Ditch Erosion	Eroded ≥ 1 ft
Drainage	Crossline Pipe	Blocked ≥ 50%, or Damaged
	Driveway Pipe	Blocked ≥ 50%, or Damaged
	Curb & Gutter	Blocked ≥ 2 in x 2 ft, or Damaged
	Catch Basin & Drop Inlet	Blocked ≥ 25%, Damaged, or Grate Problem
	Other Drainage Features	Not Functioning as designed
Roadside	Mowing	Average Grass Height
	Brush and Tree Control	Within 15' above, 10' back of ditch/shoulder
	Litter & Debris	Number of Pieces ≥ Fist-Sized
	Slope	Failures ≥ 1ft wide
	Guardrail	Damaged, or Not Functioning as designed
Traffic Control Devices	Traffic Signs	Illegible, Missing, or Obliterated
	Pavement Striping	Worn, Missing, or Obliterated
	Words and Symbols	Damaged or Missing
	Pavement Markers	Worn, Missing, or Obliterated
Environmental	Turf Condition	Bare, Dead, Diseased, Distressed, or Weedy
	Misc. Vegetation Management	Uncontrolled Growth at Signs or Guardrail

1 ft = 0.305 m; 1 in. = 25.4 mm.



Low Shoulders	High Shoulders	Lateral Ditches	Lateral Ditch Erosion
Threshold Condition Low ≥ 2 inches.	*Threshold Condition* High ≥ 1 inch.	*Threshold Condition* Blocked ≥ 50% and not functioning properly.	*Threshold Condition* Eroded ≥ 1 ft.
Total Segment Inventory Total shoulder length in the segment.	*Total Segment Inventory* Same as Low Shoulder inventory.	*Total Segment Inventory* Total ditch length in the segment.	*Total Segment Inventory* Same as Lateral Ditches inventory
Measured Amount Sum of longitudinal lengths of low shoulder.	*Measured Amount* Sum of longitudinal lengths of low shoulder.	*Measured Amount* Sum of longitudinal lengths of blocked ditch that are not functioning properly.	*Measured Amount* Sum of longitudinal lengths of eroded ditch.
Special Instructions Adjust shoulder inventory where unpaved shoulder does not exist (due to curb and gutter, median barrier, etc.).	*Special Instructions* See special instructions for Low Shoulders	*Special Instructions* Outfall ditches will not be rated. Do not deduct ordinary driveway pipe from inventory. Deduct closed systems and side-road crossline pipe from inventory.	*Special Instructions* See special instructions for Lateral Ditches.

FIGURE 2 Unpaved shoulders and ditches (1 in. = 25.4 mm; 1 ft = 0.305 m).

be revisited if there were problems or concerns with the data that had been collected.

Some randomly selected sites were not surveyed. Sites that fell within a road project under construction or were in an interchange area and sites where a portion of the road segment included a long bridge structure were not surveyed.

Reporting Survey Data

As the inspection teams walked each site, they recorded the field conditions on a form created for the purpose (Figure 7). The completed forms were faxed to the State Roadway Maintenance Unit, where the information was entered into a database.

Crossline Pipe	Driveway Pipe	Curb & Gutter	Catch Basins & Drop Inlets	Other Drainage Features
Threshold Condition Blocked ≥ 50%, or damaged.	*Threshold Condition* Blocked ≥ 50%, or damaged.	*Threshold Condition* Blocked 2 in. x 2 ft., or damaged.	*Threshold Condition* Blocked ≥ 25%, structure damage, or missing or damaged grates.	*Threshold Condition* Not functioning as designed.
Total Segment Inventory Number of crossline pipes in the segment.	*Total Segment Inventory* Number of driveway pipes in the segment.	*Total Segment Inventory* Total length of curb and gutter in the segment.	*Total Segment Inventory* Number of catch basins and drop inlets in the segment.	*Total Segment Inventory* Number of other drainage features in the segment.
Measured Amount Number of blocked or damaged crossline pipes.	*Measured Amount* Number of blocked or damaged driveway pipes.	*Measured Amount* Sum of longitudinal lengths of blocked or damaged curb and gutter.	*Measured Amount* Number of catch basins or drop inlets that are blocked, damaged, or have missing or damaged grates.	*Measured Amount* Number of other drainage features not functioning as designed.
Special Instructions Only pipes 48 inches or less will be evaluated. Lateral pipes that are side-road crossline pipes will be evaluated as a crossline pipe.	*Special Instructions* See Special Instructions for Crossline Pipe.	*Special Instructions* Only blockage that creates a diversion of water flow is to be recorded.	*Special Instructions* None	*Special Instructions* Where two drainage features are working together as a system, count them a single occurrence.

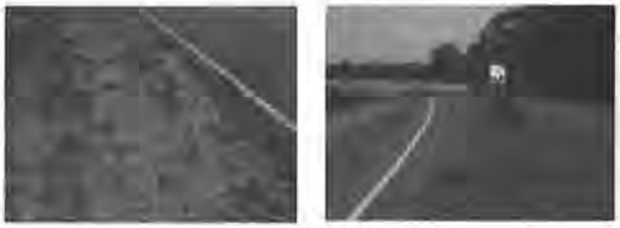
FIGURE 3 Drainage (1 in. = 25.4 mm; 1 ft = 0.305 m).

Mowing	Brush and Tree Control	Litter & Debris	Slope	Guardrail
Threshold Condition Determine the average height of the grass in the area.	*Threshold Condition* Brush and trees within 15 feet above the road, and 10 feet back of ditch or shoulder point.	*Threshold Condition* Note litter or debris that is fist-sized or larger.	*Threshold Condition* Slope failures should be noted whenever a washout or ruts $\geq$ 1 ft.	*Threshold Condition* Not functioning as designed, or damaged.
Total Segment Inventory There will be no inventory of mowing.	*Total Segment Inventory* The total length of forested area in the segment.	*Total Segment Inventory* There will be no inventory of litter and debris.	*Total Segment Inventory* The total length of outside slope in the segment.	*Total Segment Inventory* The total length of guardrail in the segment.
Measured Amount Record the average height on the survey form.	*Measured Amount* Sum of longitudinal distances where the brush and tree control zone is not clear.	*Measured Amount* Record the number of pieces of litter that are fist-sized or larger.	*Measured Amount* Sum of longitudinal lengths of eroded slope.	*Measured Amount* Sum of longitudinal length of guardrail that is not functioning as designed or has been damaged.
Special Instructions Ignore any residential mowing.	*Special Instructions* Note brush and trees that a tractor mower cannot mow, and trees beyond the control zone but still a safety concern. An exception is brush and trees that will not be removed due to public sensitivity.	*Special Instructions* If the test section has more than 200 pieces of litter, stop the count.	*Special Instructions* Measure the greatest longitudinal width of the failure during the survey.	*Special Instructions* Do not record barrier that is an old design, is only slightly damaged and still functions as designed, or is just aesthetically unpleasing.

FIGURE 4 Roadside (1 ft = 0.305 m).

Traffic Signs	Pavement Striping	Words and Symbols	Pavement Markers
Threshold Condition Note signs that are illegible, missing, or obliterated.	*Threshold Condition* Note pavement striping that is worn, missing, or obliterated.	*Threshold Condition* Note words or symbols that are worn, missing, or obliterated.	*Threshold Condition* Note pavement markers that are damaged or missing.
Total Segment Inventory The total number of traffic signs in the segment.	*Total Segment Inventory* The total length of pavement striping in the segment.	*Total Segment Inventory* The total number of word and symbol markings in the segment.	*Total Segment Inventory* The total number of pavement markers that should be in the segment.
Measured Amount Number of illegible, missing, or obliterated signs	*Measured Amount* Sum of longitudinal lengths of worn, missing or obliterated center lines, edge lines, or lane lines.	*Measured Amount* Number of words or symbols worn, missing, or obliterated.	*Measured Amount* Number of pavement markers damaged or missing.
Special Instructions Do not rate overhead signs on structures, street name signs, historic marker signs, and non-DOT signs.	*Special Instructions* Only the marking is to be measured, not the unpainted gap.	*Special Instructions* None	*Special Instructions* If pavement markers have not been installed in the segment both the Inventory and the Measured Amount will be zero.

FIGURE 5 Traffic control devices.



Turf Condition	Misc. Vegetation Management
Threshold Condition Note areas of bare, dead, diseased, distressed, or weedy turf.	*Threshold Condition* Note areas of uncontrolled vegetation growth around guardrail and signs.
Total Segment Inventory Total roadside length in the segment.	*Total Segment Inventory* The longitudinal length of all guardrail and traffic sign installations.
Measured Amount Sum of longitudinal lengths (parallel to the roadway) of poor turf growth.	*Measured Amount* Sum of longitudinal lengths of uncontrolled vegetation growth around the guardrail or signs.
Special Instructions Only the condition of turf within the normal mowing limits will be evaluated.	*Special Instructions* Use a length of 2 feet for each sign installation.

FIGURE 6 Environmental (1 ft = 0.305 m).

Besides recording the amount of each feature that exceeded the threshold condition, the teams measured the inventory of certain features existing in the section. This was necessary because a complete statewide inventory does not exist for all the features that were being surveyed. The findings from the inventory made during the maintenance survey help to estimate the statewide quantity of the various features. For example, the number of driveway pipes found within the various surveyed sites was used to estimate the total number of driveway pipes in the statewide system.

From the survey data a number could be calculated that represented the percent of each feature that exceeded the threshold condition listed in Table 1. This was done for all sites surveyed for each of the four highway systems. On the basis of the predetermined target sample size and an analysis of the results, the department was confident that the aggregate of all the sample sites represented the condition of the statewide system.

Maintenance Funding Needs

A detailed survey was conducted through the Maintenance Condition Assessment Program and the pavement condition survey to assess the condition of roadway features. These features were categorized into the previously identified six major elements. The photographs in Figure 8 illustrate some of the features recorded during the survey. For each of the four highway systems, the deficient conditions were recorded and summarized.

Level of Service

To effectively evaluate the condition of the state highway system, it was necessary to establish commonsense definitions for different levels of services, ones that could be easily understood and clearly linked to outcome performance measures. A five-level grading system was used, similar to those used in the Washington State Department of Transportation's Maintenance Accountability Process (*1*).

Level of Service A (Best)

In Level A, the roadway, bridges, and associated features are in excellent condition. Very few deficiencies are present, all systems are operational, and the overall appearance is pleasing. Preventive maintenance is a high priority in all maintenance activities.

Level of Service B (Good)

Level B is a high level of service in which the roadway, bridges, and associated features are in good condition. Very few deficiencies are present in safety and investment protection, but moderate deficiencies exist in other areas. All systems are operational. Preventive maintenance is a high priority for safety-related activities but is deferred for other areas, resulting in additional corrective maintenance activities.

Level of Service C (Fair)

In Level C, the roadway, bridges, and associated features are in fair condition. Very few deficiencies are present in safety-related activities, but moderate deficiencies exist for investment protection, and there are significant aesthetics-related deficiencies. Preventive maintenance

TABLE 2 Sample Size Requirements

	Mileage	Population Units	Number of Samples
Interstate	816	4,080	250
Primary	11,110	55,550	266
Urban	6,127	30,635	264
Secondary	48,534	242,670	267
		Total Sample Size	**1,047**

1 mi = 1.6 km.

Location

Site Number [ ] Begin MP [ ] End MP [ ] County [ ] Division [ ]

Number of Lanes [ ] Team Members [ ]

Date of Survey [ ]

Element 1a - Roadway (Flexible Pavement) -Asphalt-

Alligator Cracking	Block	Reflective	Rutting	Raveling	Bleeding	Ride Quality	Patching
N L M S	N L M S	N L M S	N L M S	N L M S	N L M S	N L M S	N L M S

Element 1b - Roadway (Rigid Pavement) -Concrete-

Shoulder: Type [P S C B U] Width [FT] Cond [L M S] Drop-off [L M S] Shldr Lane Jt. [L M S]

Surface Condition:

Patching (conc.)	Patching (asph.)	Surface Wear	Pumping	Ride
N L M S	N L M S	N L M S	N L M S	N L M S

Longitud. Cr.	Transverse Cr.	Corner Break	Spalling	Joint Seal	Faulting
N L M S	N L M S	N L M S	N L M S	N L M S	IN

Element 2 - Unpaved Shldrs and Ditches

	INVENTORY	*CONDITION*	
Low Shoulder	FT	Low ≥ 2 inches	FT
High Shoulder		High ≥ 1 inch	FT
Lateral Ditches	FT	Blocked ≥ 50% and Not Funct. as designed	FT
Lateral Ditch Erosion		Eroded ≥ 1 ft	FT

Element 3 – Drainage

	INVENTORY		*CONDITION*
Crossline Pipe	EA	Blocked ≥ 50%, or Damaged	EA
Driveway Pipe	EA	Blocked ≥ 50%, or Damaged	EA
Curb & Gutter	FT	Blocked ≥ 2 in x 2 ft, or Damaged	FT
Catch Basin & Drop Inlet	EA	Blocked ≥ 25%, Damaged, or Grate Problem	EA
Other Drainage Features	EA	Not Functioning as designed	EA

Element 4 – Roadside

	INVENTORY		*CONDITION*
Mowing	N/A	Average Grass Height	IN
Brush and Tree Control	FT	Within 15' above, 10' back of ditch/shoulder	FT
Litter & Debris	N/A	Number of Pieces ≥ Fist-Sized	PCS
Slope	FT	Failures ≥ 1ft wide	FT
Guardrail	FT	Damaged, or Not Functioning as designed	FT

Element 5 - Traffic Control Devices

	INVENTORY		*CONDITION*
Traffic Signs	EA	Illegible, Missing, or Obliterated	EA
Pavement Striping	FT	Worn, Missing, or Obliterated	FT
Words and Symbols	EA	Worn, Missing, or Obliterated	EA
Pavement Markers	EA	Damaged or Missing	EA

Element 6 – Environmental

	INVENTORY		*CONDITION*
Turf Condition	FT	Bare, Dead, Diseased, Distressed, or Weedy	FT
Misc. Vegetation Management	FT	Uncontrolled Growth at Signs or Guardrail	FT

FIGURE 7 Inventory form (1 in. = 25.4 mm; 1 ft = 0.305 m).

FIGURE 8 Examples of recorded features.

is deferred for many activities except safety-related work. Corrective maintenance is routinely practiced for all activities. A backlog of deficiencies is building and will have to be dealt with eventually, at a higher cost. Some roadway structural problems begin to appear because of long-term deterioration of the system. There is a noticeable decrease in appearance, and systems may occasionally be inoperable.

Level of Service D (Poor)

Level D is a low-maintenance service level in which the roadway, bridges, and associated features are kept in generally poor condition. Moderate deficiencies are present in safety-related activities, and there are significant deficiencies for all other activities. Very little preventive maintenance is accomplished; maintenance is reactive and places emphasis on correcting problems as they occur. A significant backlog of deficiencies will build up. Safety problems begin to appear that increase risk and liability, and significant structural deficiencies exist that accelerate the long-term deterioration of the system. The overall appearance of the system is very poor. System failures occur regularly because it is impossible to react in a timely manner to all problems.

Level of Service F (Worst)

Level F is a very low service level in which the roadway, bridges, and associated features are kept in poor and failing condition. Significant deficiencies are present in all maintenance activities. The overall appearance is not aesthetically pleasing. Preventive maintenance is not practiced for any maintenance activities. Maintenance is totally reactive and places emphasis on correcting problems as they occur. Significant backlogs of maintenance deficiencies exist. Excessive safety problems occur. A backlog of system failures occurs because it is impossible to react in a timely manner to all problems.

Acceptable Levels of Service

Obviously, it would be desirable for the entire highway system to be maintained at Level A. However, it would be impractical, if not impossible, to achieve this level of service for all highways. On the other hand, there are valid reasons for some of the features to be maintained at a high level of service, especially those features associated with safety, such as guardrails. Other features, such as pavement striping, low shoulders, raised pavement markers, and pavements, are safety items as well and should be maintained at a high level. The lower the level of service of these features, the poorer the condition and the greater the potential for accidents.

To relate the five levels of service to performance standards and condition ratings, extensive research was conducted of the procedures used in other state departments of transportation. A work session was held with field representatives from each of NCDOT's 14 divisions to provide input based on their knowledge of the highway system and its maintenance condition. Baselining what other agencies have done and using input from the professional staff, various levels of service were established for each maintenance feature. An example of the performance measure for the primary highway system is provided in Figure 9.

ELEMENT 1			Service Level					
Roadway Pavement			A	B	C	D	F	Acceptable Level of Service
Activities	Condition Indicators	Performance Measures	Threshold	Threshold	Threshold	Threshold	Threshold	
Pavement Maintenance	Pavement Condition Rating	PCR	98	93	86	70	< 70	C

ELEMENT 2			Service Level					
Unpaved Shoulders and Ditches			A	B	C	D	F	Acceptable Level of Service
Activities	Condition Indicators	Performance Measures	Threshold	Threshold	Threshold	Threshold	Threshold	
Low Shoulder	Low ≥ 2 inches	FT	1%	5%	8%	11%	> 11%	C
High Shoulder	High ≥ 2 inches	FT	1%	4%	6%	10%	> 10%	C
Lateral Ditches	Blocked ≥ 50% & not funct. as designed	FT	2%	6%	9%	12%	> 12%	C
Lateral Ditch Erosion	Eroded ≥ 1 ft	FT	1%	2%	3%	4%	> 4%	A

ELEMENT 3			Service Level					
Drainage			A	B	C	D	F	Acceptable Level of Service
Activities	Condition Indicators	Performance Measures	Threshold	Threshold	Threshold	Threshold	Threshold	
Crossline Pipe	Blocked ≥ 50%, or Damaged	EA	2%	7%	11%	15%	> 15%	C
Driveway Pipe	Blocked ≥ 50%, or Damaged	EA	10%	15%	25%	35%	> 35%	C
Curb & Gutter	Blocked ≥ 2 in x 2 ft, or Damaged	FT	2%	5%	7%	11%	> 11%	C
Catch Basin & Drop Inlet	Blocked ≥ 25%, Damaged, or Grate Problem	EA	2%	5%	8%	12%	> 12%	C
Other Drainage Features	Not Functioning as designed	EA	2%	6%	9%	12%	> 12%	C

ELEMENT 4			Service Level					
Roadside			A	B	C	D	F	Acceptable Level of Service
Activities	Condition Indicators	Performance Measures	Threshold	Threshold	Threshold	Threshold	Threshold	
Mowing	Average Grass Height	IN	6	8	10	14	> 14	C
Brush & Tree Control	Within 15' above, 10' back of ditch/shoulder	FT	5%	10%	15%	25%	> 25%	C
Litter & Debris	Number of Pieces ≥ Fist-Sized	PCS	30	60	120	200	> 200	C
Slope	Failures ≥ 1 ft wide	FT	1%	3%	5%	7%	> 7%	B
Guardrail	Damaged, or Not Functioning as designed	FT	1%	3%	5%	7%	> 7%	A

ELEMENT 5			Service Level					
Traffic Control Devices			A	B	C	D	F	Acceptable Level of Service
Activities	Condition Indicators	Performance Measures	Threshold	Threshold	Threshold	Threshold	Threshold	
Traffic Signs	Illegible, Missing, or Obliterated	EA	1%	3%	6%	8%	> 8%	C
Pavement Striping	Worn, Missing, or Obliterated	FT	2%	5%	8%	11%	> 11%	C
Words & Symbols	Worn, Missing, or Obliterated	EA	1%	4%	8%	11%	> 11%	C
Pavement Markers	Damaged or Missing	EA	5%	10%	15%	20%	> 20%	B

ELEMENT 6			Service Level					
Environmental			A	B	C	D	F	Acceptable Level of Service
Activities	Condition Indicators	Performance Measures	Threshold	Threshold	Threshold	Threshold	Threshold	
Turf Condition	Bare, Dead, Diseased, Distressed, or Weedy	FT	3%	7%	11%	15%	> 15%	C
Misc. Vegetation Mgmt.	Uncontrolled Growth at Signs or Guardrail	FT	5%	10%	15%	25%	> 25%	C

FIGURE 9 Primary highway system maintenance performance measures (1 in. = 25.4 mm; 1 ft = 0.305 m).

SURVEY FINDINGS

The results of the 1998 survey were compared with minimum acceptable levels. One level of analysis determined the extent to which each feature exceeded the previous defined threshold values from Table 1. Figure 10 provides a graphical representation of the results of the primary highway system. Another assessment compared the survey findings with the previously identified levels of service (Figure 9) to determine the average service level for each feature. An example of this comparison is shown in Figure 11, which illustrates the average statewide level of service by maintenance activity on the primary highway system.

The level of service figures generated from the statewide 1998 maintenance assessment survey illustrated that a few activities were being maintained at an acceptable level. However, many activities were being maintained at a poor D or unacceptable F level of service because of a lack of funds. Also, as was mentioned, some features must be

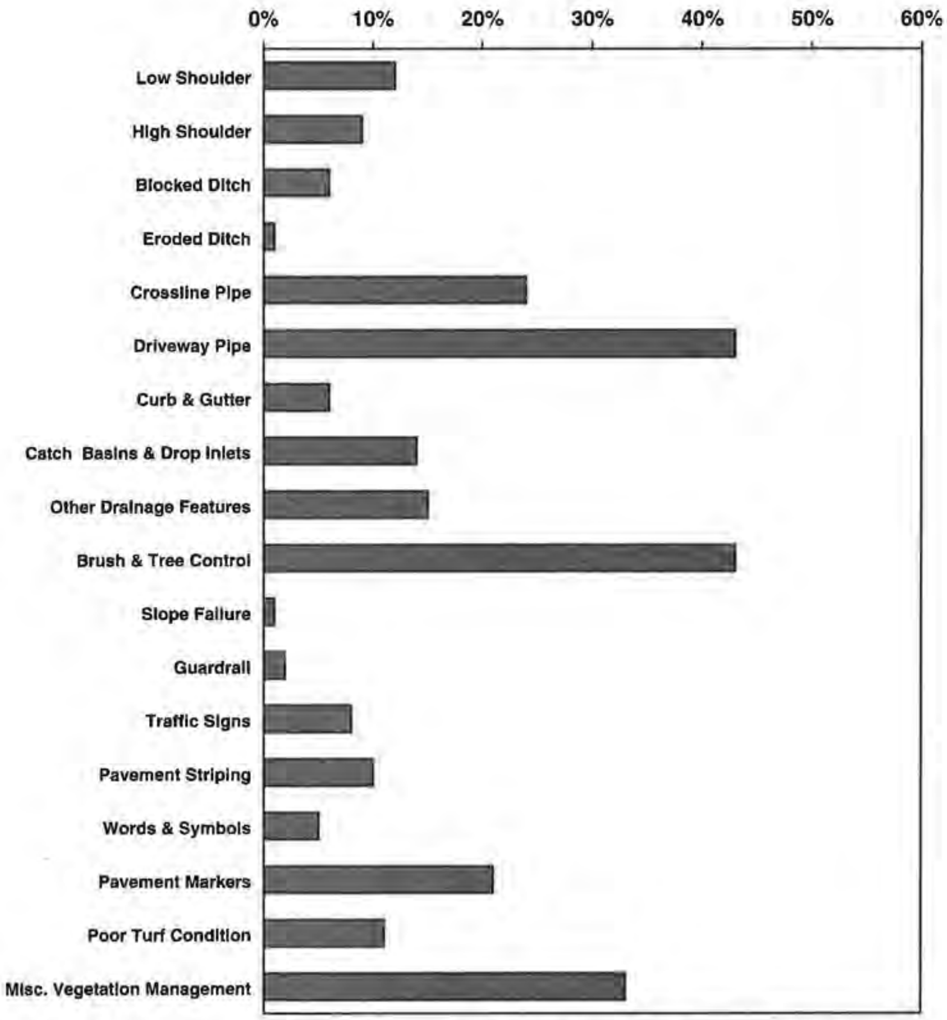


FIGURE 10 **Percentage of features exceeding threshold value for primary highway system, 1998 survey.**

maintained at a high level of service because of safety concerns and considerations.

A main objective of the study was to estimate the funding required to maintain the state system of highways at an acceptable level. For each highway system (Interstate, primary, urban, secondary), funding levels were estimated to achieve the various levels of service. An example is shown in Figure 12, where the required maintenance funding is given (for all features of the primary system) to meet the various service levels. These costs were generated for all features in each highway system. After comparing the actual feature service level with the acceptable level of service, the cost to meet the acceptable level could be determined. Table 3 is a summary of the costs estimated to achieve a statewide acceptable level of service for all four highway systems.

With data from the 1998 survey, it was estimated that it would cost $316.8 million to fund the performance-based activities in order to provide an acceptable level of service. It should be noted that the survey was conducted statewide and the results cannot be applied specifically to a county, district, or division area.

Recommendations

An analysis of the condition of the highway system was made by using the maintenance condition assessment program. From this, the maintenance activities necessary to achieve the various levels of service were determined, along with their estimated costs. To provide the citizens of North Carolina with a safe and uniformly maintained highway system, cost estimates were itemized, reflecting

Maintenance Activity	LOS A	LOS B	LOS C	LOS D	LOS F
Roadway Pavement					
Pavement			○	□	
Unpaved Shoulders and Ditches					
Low Shoulder			○		□
High Shoulder			○	□	
Lateral Ditches			□ ○		
Lateral Ditch Erosion	○ □				
Drainage					
Crossline Pipe			○		□
Driveway Pipe			○		□
Curb & Gutter			□ ○		
Catch Basin & Drop Inlet			○		□
Other Drainage Features			○		□
Roadside					
Mowing			○□		
Brush and Tree Control			○		□
Litter & Debris			○	□	
Slope		□ ○			
Guardrail	○	□			
Traffic Control Devices					
Traffic Signs			○	□	
Pavement Striping			○	□	
Words and Symbols			□ ○		
Pavement Markers		○			□
Environmental					
Turf Condition			○	□	
Misc. Vegetation Management			○		□

○ - Acceptable Service Level   □ - Average Feature Service Level

FIGURE 11 Maintenance levels of service for primary highway system.

a need to achieve at least a C level of service. However, some of the cost estimates reflected a higher level of service because of safety concerns and considerations.

On the basis of these service levels, NCDOT developed a statewide annual maintenance funding plan, shown in Table 4. This plan not only would allow the establishment of a sound maintenance program that would provide an acceptable level of service but also address the backlog of maintenance needs that has been building over the years.

By adding all the other maintenance programs and obligations, such as statewide programs, disasters and emergencies, routine bridge maintenance programs, contract resurfacing, and contract resurfacing backlog costs, to the \$316.8 million shown in Table 3, NCDOT estimated that its total highway maintenance budget should be approximately \$705 million for the 1999–2000 fiscal year. In contrast, the department's budget for the previous year was \$462 million, some \$243 million shy of the mark.

Summary and Conclusions

To evaluate the condition of the state highway system in North Carolina, a maintenance assessment program has been developed and implemented by NCDOT. Several objectives were satisfied, including the following:

- The condition of the state highway system has been measured and assessed.
- A framework that links work activity expenditures to actual highway feature condition has been developed.
- The funds necessary to maintain the system at various service levels has been calculated.
- The funds necessary to maintain the system at an acceptable level has been computed.
- Highway features that failed to meet the acceptable maintenance condition have been identified.
- A methodology has been established to validate that the condition of the highway system is directly related to the funding level and to demonstrate that when funding levels are inadequate, the highway system's condition will suffer.
- Attention has been brought to the condition of the highway system and the need to adequately fund maintenance activities.
- A mechanism by which to communicate clearly to the state legislature the condition and funding needs of the highway system has been developed.

Primary Highway System				
Maintenance Activity	Total Cost Level of Service A	Total Cost Level of Service B	Total Cost Level of Service C	Total Cost Level of Service D
Pavements				
Subtotal	$ 25,893,549	$ 22,436,529	$ 18,020,129	$ 13,543,829
Shoulders & Ditches				
Low Shoulder	$ 8,587,321	$ 7,639,441	$ 6,928,531	$ 6,217,621
High Shoulder	$ 7,638,892	$ 6,927,982	$ 6,454,042	$ 5,506,162
Lateral Ditches	$ 4,777,563	$ 3,066,043	$ 1,782,403	$ 498,763
Lateral Ditch Erosion	$ 99,491	$ 60,340	$ 35,373	$ 16,825
Subtotal	$ 21,103,268	$ 17,693,807	$ 15,200,350	$ 12,239,371
Drainage				
Crossline Pipe	$ 6,244,931	$ 5,801,025	$ 5,445,900	$ 5,090,775
Driveway Pipe	$ 3,685,529	$ 3,309,449	$ 2,557,289	$ 1,805,129
Curb & Gutter	$ 178,125	$ 149,505	$ 130,425	$ 92,265
Catch Basins & Drop Inlets	$ 1,388,319	$ 1,267,884	$ 1,147,449	$ 986,869
Other Drainage Features	$ 2,704,330	$ 2,130,830	$ 1,700,705	$ 1,270,580
Subtotal	$ 14,201,234	$ 12,658,692	$ 10,981,767	$ 9,245,617
Roadside				
Mowing	$ 12,253,786	$ 10,252,726	$ 6,250,606	$ 4,249,546
Brush & Tree Control	$ 4,433,780	$ 4,324,625	$ 4,215,470	$ 3,997,160
Litter & Debris	$ 6,546,137	$ 4,364,091	$ 2,909,394	$ 1,454,697
Slope Failure	$ 409,897	$ 343,285	$ 295,875	$ 262,475
Guardrail	$ 1,676,807	$ 680,449	$ 515,489	$ 390,779
Subtotal	$ 25,320,406	$ 19,965,176	$ 14,186,834	$ 11,960,139
Traffic Control Devices				
Traffic Signs	$ 9,792,386	$ 8,692,386	$ 7,042,386	$ 5,942,386
Pavement Striping	$ 5,262,479	$ 4,311,671	$ 3,360,863	$ 2,410,055
Words & Symbols	$ 935,804	$ 709,495	$ 407,749	$ 181,439
Pavement Markers	$ 1,316,865	$ 1,154,378	$ 991,891	$ 829,404
Subtotal	$ 17,307,534	$ 14,867,930	$ 11,802,889	$ 9,363,285
Environmental				
Turf Condition	$ 5,613,590	$ 3,701,430	$ 1,789,270	$ 1,469,270
Misc. Vegetation Management	$ 1,188,344	$ 1,114,744	$ 1,041,144	$ 893,944
Subtotal	$ 6,801,934	$ 4,816,174	$ 2,830,414	$ 2,363,214
Total Funding to Achieve LOS	**$ 110,627,924**	**$ 92,438,308**	**$ 73,022,383**	**$ 58,715,455**

FIGURE 12 Primary highway system road maintenance funding matrix table.

By implementing a maintenance condition program and obtaining the desired level of funding, NCDOT will be able to shift from a reactive mode of fixing problems to a proactive mode of preventing them. Eventually, this will lead to greater customer satisfaction at unit costs below those currently experienced by the agency, permit the department to target funds to address highway features that are in poor condition, identify areas requiring additional employee skills or areas where employees can be shifted, and redirect funding to achieve a uniform level of service throughout the state.

Future Work and Objectives

The 1998 maintenance assessment study laid the groundwork for an overall total quality assessment and assurance program for NCDOT. Beyond providing information for funding requests and identifying features in poor maintenance condition, it is anticipated that the system may be expanded to provide results on a division level for allocation of resources. In 1999, the study was repeated to validate the first study's results and to also conduct an evaluation of one of the 14 divisions. The results of the 1999 survey for the primary highway

TABLE 3 Estimated Cost to Achieve Acceptable Statewide Level of Service

Maintenance Activity	Actual Expenditures	Funds Needed
Pavement Maintenance		
Pavement	$56,096,877	$123,246,298
Subtotal	$56,096,877	$123,246,298
Shoulders & Ditches		
Low Shoulder	$14,482,939	$20,021,709
High Shoulder	$14,200,311	$18,598,583
Lateral Ditches	$7,440,081	$7,808,887
Lateral Ditch Erosion	$601,842	$356,864
Subtotal	$36,725,173	$46,786,043
Drainage		
Crossline Pipe	$11,938,509	$21,506,565
Driveway Pipe	$4,737,222	$15,146,686
Curb & Gutter	$1,141,374	$1,076,484
Catch Basins & Drop Inlets	$2,257,001	$4,301,579
Other Drainage Features	$2,257,001	$5,304,325
Subtotal	$22,331,107	$47,335,639
Roadside		
Mowing	$20,159,558	$21,016,878
Brush & Tree Control	$11,053,151	$15,710,234
Litter & Debris	$4,543,160	$5,382,087
Slope Failures	$1,433,069	$1,057,931
Guardrail	$2,700,633	$4,062,950
Subtotal	$39,889,571	$47,230,079
Traffic Control Devices		
Traffic Signs	$16,224,996	$16,281,988
Pavement Striping	$9,832,715	$21,576,477
Words & Symbols	$1,985,337	$4,945,665
Pavement Markers	$314,569	$3,094,008
Subtotal	$28,357,617	$45,898,138
Environmental		
Turf Condition	$2,364,827	$3,403,605
Misc. Vegetation Management	$3,035,977	$2,869,543
Subtotal	$5,400,804	$6,273,148
Total Routine Maintenance Funding	**$188,801,149**	**$316,769,344**

TABLE 4 Statewide Annual Maintenance Funding Plan, Fiscal Year 1999–2000

MAINTENANCE PROGRAMS	FY 1999-2000 Funding (millions)
Statewide Programs	$10.33
Disasters/Emergencies	$32.00
Routine Road Maintenance	
a. Reoccurring Programs	$72.08
b. Performance Based Programs	$316.78
Routine Bridge Maintenance	
a. Reoccurring Programs	$24.64
b. Performance Based Programs	$19.74
Routine Maintenance Backlog	$22.50
Contract Resurfacing	$200.00
Contract Resurfacing Backlog	$7.00
GRAND TOTAL	**$705.07**

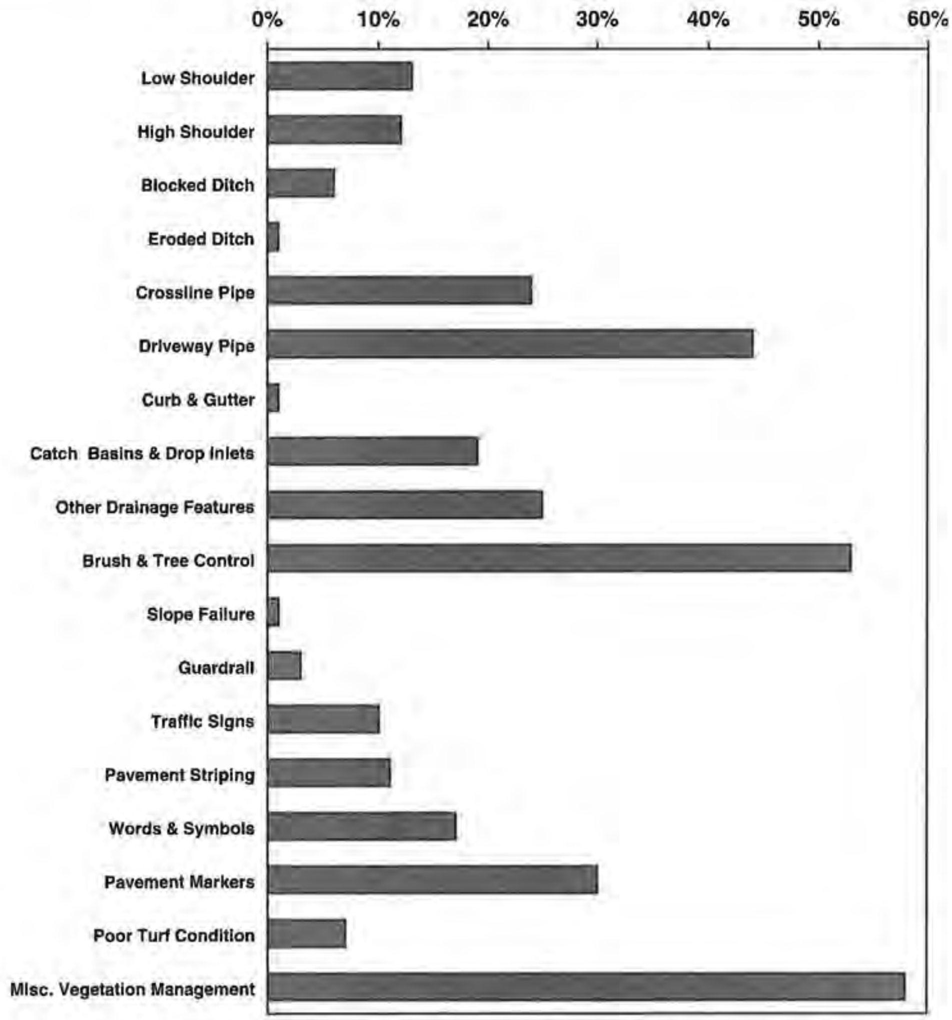


FIGURE 13 Percentage of features exceeding threshold value for primary highway system, 1999 survey.

system, shown in Figure 13, were very similar to the 1998 findings.

The 1999 North Carolina General Assembly established a task force consisting of legislative and community leaders to investigate current funding deficiencies and recommend potential avenues to address the shortfall in transportation funding. The task force will complete its work in time for the 2001 legislative session. Although this will not benefit the 2000–2001 fiscal budget year, the department will continue to evaluate the condition of the state highway system and seek additional sources of funds to address deficiencies identified in the study.

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Continuing Quality Improvements in Pennsylvania Highway Maintenance

Gary L. Hoffman

The Pennsylvania Department of Transportation (PennDOT) continues to be on a quality improvement journey that began more than 20 years ago. PennDOT is responsible for maintaining and operating the fifth-largest state transportation system in the nation, with 64 000 centerline-km or 161 000 lane-km (40,000 centerline-mi or 100,000 lane-mi) of pavement and 25,000 bridges. This system carries about 16 percent commercial truck traffic, the highest of any state in the northeastern United States. PennDOT is using the seven Baldrige precepts to improve many of its operations: leadership, strategic planning, customer and market focus, information and analysis, human resource development and management, process management, and business results. In 1998 PennDOT entered the pilot phase of the Baldrige journey. The traditional process included the preparation of a 50-page organization review package (ORP) providing an examiner with a detailed description of the organization and its processes. Each PennDOT bureau and engineering district began preparing ORPs in the fall of 1998, and each was scored by about 15 of the 125 trained and certified internal Baldrige examiners. PennDOT's "Agility" Program follows a strategy designed to enable organizations to adapt and thrive in an era of continuous change, an immediate challenge for the department. The self-assessment gap analysis and Agility initiatives, along with the other Baldrige approaches, are driving positive change in the maintenance area. Internal indicators like lower system pavement roughness, better line striping, equipment fleet optimization, and dollars saved attest to the success of these changes.

Pennsylvania Department of Transportation, 7th Floor Forum Place, 555 Walnut Street, Harrisburg, PA 17101-1900.

The Pennsylvania Department of Transportation (PennDOT) continues on a quality improvement journey that began more than 20 years ago when, in 1978, Governor Dick Thornburgh named Thomas Larson State Secretary of Transportation and charged him with revitalizing the agency.

The PennDOT quality journey has included numerous initiatives, most of which have had significant impact in the maintenance community, which is the largest organization in the department (see Figure 1).

Starting with quality circles in the early 1980s, moving to quality teams in the mid-1980s, through maintenance benchmarking in the mid-1990s, to the Baldrige efforts of today, PennDOT has positively changed how maintenance and operations activities are accomplished—and PennDOT customers are noticing the improvements.

Today, under the leadership of Pennsylvania Secretary of Transportation Bradley L. Mallory and with the support of Governor Tom Ridge, PennDOT espouses the Baldrige criteria and is using them to change the corporate culture.

Organization Statistics and Structure

PennDOT is responsible for maintaining and operating the fifth-largest state transportation system in the nation. Overall, PennDOT is responsible for 64 000 centerline-km or 161 000 lane-km (40,000 centerline-mi or 100,000 lane-mi) of pavement and 25,000 bridges. This state system carries about 16 percent commercial truck traffic, the highest of any state in the northeastern United States.

FIGURE 1 PennDOT quality journey.

Because of its age and diversity of design, the highway system in Pennsylvania is very fragile and requires constant managed care. The administration and the secretary of transportation recognize the importance of maintaining this infrastructure and have given maintenance ample support. PennDOT has invested about $1 billion into maintenance in each of the last 3 years. In fact, a recent report (*1*) lists PennDOT as the highest-ranked state department of transportation when the percentage (37 percent) of the total budget that is spent on maintaining existing facilities is compared.

To meet the challenge of maintaining and preserving this large and diverse infrastructure, PennDOT is organized into a central office and 11 fairly autonomous engineering district offices. Each district office has an assistant district engineer for maintenance who is responsible for three to eight county maintenance organizations.

PennDOT's county maintenance forces vary from 20 to 220 employees. Statewide, 7,000 of PennDOT's 12,300 employees work in maintenance-related functions, and 6,500 of these are at the county level.

Baldrige Initiative

PennDOT uses Baldrige criteria to improve many of its operations. The Baldrige initiative is a general set of principles that may be applied to improve any business or business group. The seven Baldrige precepts are leadership, strategic planning, customer and market focus, information and analysis, human resource development and management, process management, and business results. Each precept is important and necessary to the good management of any organization.

The Baldrige initiative takes these seven principles and puts them into a continuous or closed loop. Leadership sets direction based on customer input; processes are defined; and business result measures are established and monitored. Feedback mechanisms are established to tell leaders where and how to make changes for continuous improvement based on these defined processes and business results.

These concepts were used to establish eight strategic focus areas (SFAs) or business groups. These are

- Maintenance first,
- Quality of life,
- Mobility and access,
- Customer focus,
- Innovation (technology),
- Safety,
- Leadership, and
- Relationship building.

The SFAs were established through numerous focus groups that included partners, stakeholders, customers, and employees. Subsequently, 21 strategic objectives, each supporting one of the SFAs and each having specific appropriate metrics, were established. These strategic objectives and metrics were determined with much input from employees, who were champions and were responsible for implementing the objectives.

It is important to note the prominence of the "maintenance first" and "mobility and access" SFAs, both of which deal primarily with the preservation and operations of the existing infrastructure. The department uses a broad definition of maintenance to include structural improvements on existing alignment.

A number of the Baldrige initiatives are under way in the maintenance area. These maintenance initiatives include foreman training and certification, the maintenance management benchmarking system, the maintenance quality assurance–quality control process, the self-assessment gap analysis (SAGA), and the Agility (recasting) process.

SAGA

In 1998, PennDOT entered the pilot phase of the Baldrige journey. The traditional Baldrige process included the preparation of a 50-page organization review package (ORP), which provides an examiner with a detailed description of the organization and its processes.

Each PennDOT bureau and engineering district began preparing an ORP in the fall of 1998, and each was scored by about 15 of the 125 trained and certified internal Baldrige examiners. (PennDOT's entire executive staff and top managers are certified Baldrige examiners.)

At the same time the department was implementing this traditional ORP process, it learned of the SAGA process from AMP, Inc., an international electrical connector company based in Harrisburg, Pennsylvania. The SAGA process is an intense 3-day workshop in which an organization's employees, partners, suppliers, and customers take a close look at organization operations. They assess organizational strengths and opportunities relative to the Baldrige criteria. Essentially, the SAGA workshop provides the organization the means to verbally "write" a less formal ORP in 3 days, to determine three to seven gaps, and to form gap closure teams.

After several county maintenance organizations piloted the SAGA process, it was determined that the SAGA workshop was a more appropriate tool for the county organization than was the more traditional ORP process. The written ORP process is extremely labor intensive and time-consuming to prepare. Another disadvantage of the ORP preparation process is that it involves a relatively small percentage of the workforce in an organization. The ORP approach may also require more discipline and technical expertise than is generally found in the county maintenance organizations.

Conversely, the SAGA process can involve 50 to 75 percent of the personnel in an organization in a facilitated, structured, concise group-dynamics effort that is done verbally. Technographers are used to record strengths and opportunities, which are subsequently prioritized.

The Bureau of Maintenance and Operations dedicated two full-time employees to coordinate and implement the SAGA process in 58 county organizations in a 30-month period beginning in August 1998. About 55 employees are trained and certified SAGA examiners. A few examiners and trained facilitators guide and standardize the process in each county workshop.

Before the 3-day workshop, all of the proposed participants complete a 1-day training session. These training sessions are designed to familiarize the attendees with the SAGA process, the Baldrige criteria, and the gap closure concepts. Additionally, training exercises are conducted to increase the participants' familiarity and comfort with the process.

PennDOT completed 20 county SAGA workshops in 1999, and at the time of this writing in 2000, 12 more workshops have been completed. By the end of 2000, 45 workshops will have been completed. Typically, about 180 opportunities and 120 strengths are identified in these workshops. The long list of opportunities is prioritized at the end of the workshop, and the top three to seven opportunities (the "vital few") are each slated for action by select teams.

This shortlisting process does not discard the rest of the 180 opportunities. "Quick kills" are identified and addressed so early accomplishments can energize the group toward success in some of the more difficult, longer-term actions. About 70 vital few opportunities or gaps have been identified so far. Some of these are as follows:

- Implement fleet management process with operator input.
- Improve work plan process with employee input.
- Formalize training and certification programs for trades employees.
- Streamline the purchasing process, particularly for materials.
- Implement aggressive communications efforts internally and externally on work zone locations.
- Develop a comprehensive electronic data processing and telecommunications plan at the county level.
- Segment internal and external customers and request their input.
- Communicate strategic plan and objectives to all department employees.
- Provide more flexibility in work schedule and hours.

The process does not stop once the workshop is over. Action plans with milestones are established by the gap closure teams addressing the vital few opportunities. The full-time central office coordinators then assess gap closure team progress at 6-month intervals. Resources are provided as necessary to ensure successful gap closures.

The overall assessment of the SAGAs conducted to date indicates that they are meeting the goals of improving organizational performance and capabilities and of delivering ever-improving value to customers. Another key benefit of the SAGA process is the open communication among the stakeholders, including management, employees, and external partners. The team spirit that evolves and the focus on improvement are remarkable.

AGILITY

PennDOT's "Agility" program began after Secretary Mallory visited the Iacocca Institute at Lehigh University in Bethlehem, Pennsylvania. Agility is a strategy designed to enable organizations to quickly adapt and thrive in an era of continuous change, and this became an immediate challenge for PennDOT.

The Iacocca Institute was contracted by PennDOT to help launch the Agility pilot by emphasizing the principles of Agility and their application to the department's maintenance organization.

The basic tenets of the Agility process are (*a*) to empower the employees at all levels to take advantage of opportunities to improve efficiency and effectiveness; (*b*) to provide the opportunity for customers to communicate, and then to react quickly to their needs; (*c*) to develop new partnerships with local governments and community groups; (*d*) to foster improved cooperation between management and the American Federation of State, County and Municipal Employees (AFSCME); and (*e*) to create an adaptive organization and culture.

One of the most important benefits of the Agility process is that it has allowed foremen to actually manage their crews. About 500 people make up PennDOT's team of foremen, who are all first-line maintenance supervisors and are members of AFSCME, the primary labor union representing the department.

Before Agility, assistant county managers had very tight control over the daily activities of the crews, so much so that many foremen were not expected or given the opportunity to supervise their crews. With the implementation of Agility, foremen were empowered to help plan their weekly activities, take personnel actions to ensure sufficient crew makeups, order materials, and coordinate with vendors and contractors on a day-to-day basis to accomplish the work plan.

The assistant county managers, who transferred these activities to the foremen, now are in a coaching, quality assurance, and training position for the foremen and crews. This delegation of authority also provided the assistant county managers with more time to spend developing partnerships with local governments and responding to customer needs.

Another important change that occurred through Agility was the ability to trade maintenance services with local governments and community groups to effect overall efficiency gains. PennDOT now can enter into very short and simple agreements to exchange services where the customer and PennDOT both benefit. By Pennsylvania law, the department cannot divert dedicated motor license funds to the local governments in a way that will cause an inequality in their distribution, which is done according to statute.

Costs borne by the department for maintenance activities or services provided must be reciprocated with services or activities equal in value. Some examples of these agreements are as follows:

- The department paints traffic lines in exchange for roadside mowing.
- The department provides surplus snowplow equipment or winter materials to a local government in exchange for snowplowing services on state-maintained routes within the local government boundaries.
- The department provides parking lot sealing for a volunteer fire company in exchange for bridge washing services.

Some organizations with which agreements have already been executed are local governments, the federal government, other state departments, state universities, volunteer fire companies, municipal authorities, and school districts.

More than 1,080 agreements are in place in the state's 67 counties, and the savings are more than $4.7 million from 289 work plans. The department now has agreements with about 30 percent of the local governments in the state. New or enriched partnerships are being developed every week.

A third benefit of the Agility initiative is the recognition of and reaching out to customers, ensuring that the department establishes objectives to meet their needs and expectations. Customers are involved through routine communication mechanisms in every county. Standing customer advisory boards have been established in many counties, allowing customers to become familiar with department businesses and to actively participate in decisions regarding projects and other parts of the operations.

Public surveys, media spots, presentations at public meetings and civic groups, and computerized complaint-tracking systems have become effective ways to communicate information in both directions. The sense and the reality at the local level is that PennDOT is accessible and that PennDOT is listening.

Still another outcome of the Agility changes is the improved cooperation and shared goals with AFSCME. The department has made substantial organizational changes and placed an emphasis on the efficient performance of employees by providing tools and training and by removing policies and procedures that inhibit flexibility and success. The union and management both recognize that the overarching goal is to meet customer needs as efficiently as possible. An example of a changed

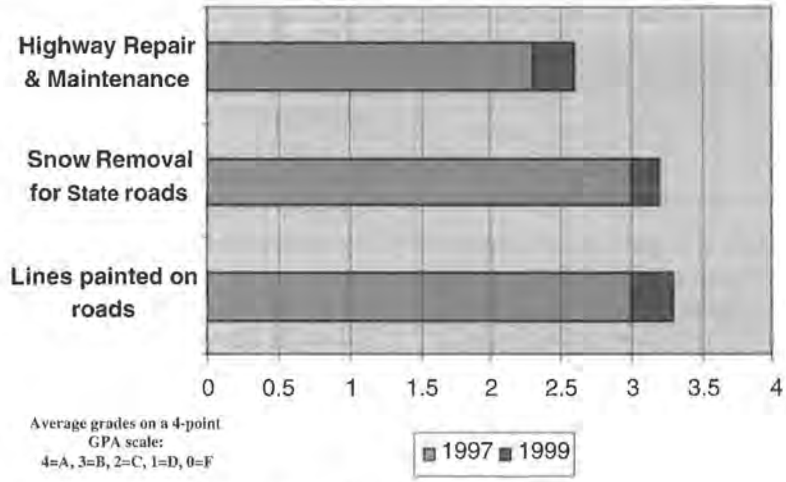


FIGURE 2 Quality grades for PennDOT services.

rule is the ability for work crews to cross county lines where it makes logistical sense to do so. Employees are compensated accordingly for travel time and expenses.

Results

The SAGA and Agility initiatives, along with the other Baldrige approaches in maintenance, are driving positive change in the maintenance business. Internal indicators like significantly lower system pavement roughness, better line striping, equipment fleet optimization, and dollars saved attest to the success of these changes.

Also, customers are telling PennDOT that they see the improvements. The biannual QUIK surveys are telephone surveys to 1,300 randomly selected customers. A comparison of the results of the 1999 survey with those of the 1997 survey indicates that PennDOT has made improvement in 18 of 24 categories.

The most improved category was pavement maintenance (Figure 2). The most telling statistic (Figure 3) is that in 1997, 55 percent of the surveyed customers said they thought PennDOT was doing a significantly better job than it was 5 years earlier. In 1999, about 67 percent of the respondents to the same questions indicated that PennDOT was doing significantly better. This shift in the public's perception is significant by any statistical test and is due in large part to these quality initiatives.

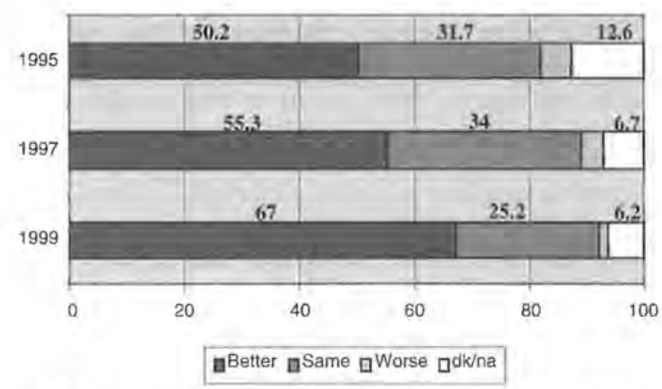


FIGURE 3 PennDOT quality compared with 5 years ago.

Reference

1. Hartgen, D. T., and N. J. Lindeman. *TEA-21's Promise: Comparative Performance of State Highway Systems, 1984–1998.* Transportation Report 195. University of North Carolina, Charlotte, 2000.

Quality of Maintenance Materials

Jeffrey A. Swan

Ascertaining the quality of materials purchased for use in highway maintenance is a continuing challenge, especially with the procurement processes used by governmental agencies. Material quality control ensures that maintenance personnel get the material that will meet their needs and be durable, workable, and economical. The current procurement process in Arizona appears to stand in the way of achieving the goal of purchasing quality materials. The process, which has statutory basis in Arizona, was adopted to ensure that what is needed can be bought at the lowest possible price. The concept has merit, but the implementation details are a major issue. The rules and regulations that were designed to avoid conflicts of interest, ensure competition, and prevent state employees from benefiting from awarded contracts make it very difficult to get the products desired. In contrast to the procurement process used to purchase materials for maintenance, the contracting process used to construct highway facilities has a greater quality control and assurance program, along with the flexibility to adjust to the changing conditions of a construction project. The specifications are very project specific and in most cases are thoroughly researched and tested to ensure that they will sufficiently meet the design life of the project. Reviewed are the things being done in Arizona to close the gap between construction-materials quality control and maintenance-materials quality control. The procurement process is reviewed, and some ongoing research activities that relate to maintenance material quality are outlined. Also considered is what the Holbrook district is doing to address material quality at the local level.

Arizona Department of Transportation, Holbrook District, 2407 East Navajo Boulevard, Holbrook, AZ 86025-1828.

The process for procuring materials is difficult to understand and even more difficult to relate to maintenance personnel. Table 1 outlines the process as generally used by the Arizona Department of Transportation (ADOT) procurement department (Procurement).

Table 1 shows that to get something on the street and awarded takes up to 3 months, assuming there are no questions or problems with the way specifications are written.

The specification that is provided to Procurement normally is written by individuals who have very little background in material specifications. In some cases, the specifications used are lifted from ADOT's standard specifications used for construction projects, and sometimes the applicable standard drawing is used as part of the request. Often the requestor is the maintenance supervisor, who has limited knowledge of and training in specifying needed material. Thus, in many instances the product that is specified does not fully meet the need of the requestor.

Procurement codes require agency personnel to buy products from the "lowest responsible bidder," which means that the low bid meets the requirements and specifications outlined in the bid package. If the material specified is not well defined, then the low bidder will provide the product that most closely fits the specifications in the bid package.

The actual material specified for a maintenance activity usually does not fully meet the need. The real issues then are, How do we know what we are getting? and, Is what we get really working?

TABLE 1 ADOT Procurement Process

RFP Ideal Timeline	Week 1	Week 2	Week 3	Week 5	Week 7	Week 8	Week 10	Week 11
Initiation of purchase								
Requester writes statement of work								
Requisition is entered into system								
Procurement reviews both requisition and statement of work								
Procurement drafts solicitation and returns for review								
Changes are made to the draft by the requester and returned to Procurement								
Procurement makes changes and completes final solicitation document								
Advertisement								
Pre-bid/Pre-offer conference								
Bids open (minimum of 2 weeks from last advertisement)								
Evaluation meetings if required								
Tentative award (Period to verify insurance, etc.)								
Award notice								
Post award meeting								

Current Research Projects and Programs

Current attempts to help maintenance personnel obtain quality material include statewide research projects in pavement maintenance and preapproval of proprietary products for use by maintenance forces. A maintenance products evaluation committee and a new research project address procurement processes.

Pavement Maintenance

The Strategic Highway Research Program investigated the cost-effectiveness of several pavement surface treatment alternatives. However, the resulting data and analysis have not provided needed techniques and information for developing and promoting cost-effective pavement maintenance strategies.

The effectiveness of many maintenance activities, such as pothole repair, crack sealing, flushing, and surface treatments, varies from area to area, and their performance is difficult to quantify at a network or project level. In addition, ADOT makes considerable use of asphalt rubber. The preventive maintenance activities could be significantly different for these roadways. ADOT must establish procedures for the effective treatment of these products.

Many proprietary products have potential for providing cost-effective maintenance treatments. However, low-bid procurement processes often inhibit the use of these products because of a lack of available information with which to develop justifications based on public interest.

Additionally, innovative contracting procedures, such as warranted work, currently are difficult to implement. Evaluation of the current laws and procurement procedures is necessary to determine how some of these alternative procurement processes can be utilized.

The objectives of this project are to (*a*) identify the maintenance surface treatment alternatives suitable for evaluation by ADOT; (*b*) develop consensus for which alternatives to test; (*c*) determine the performance and cost-effectiveness of these treatments; and (*d*) identify procurement issues that inhibit effective pavement maintenance and then recommend solutions to these issues. This will be accomplished by developing an experimental design and constructing and evaluating test sections. To date, approximately 60 test sections have been constructed.

Product Resource Investment, Deployment, and Evaluation

During the construction of many projects, proprietary products are installed as permanent features of the highway. Once these highway segments are turned over to the ADOT maintenance department, personnel find it extremely difficult to buy replacement parts for these devices, because of language in the state's procurement code and because of ADOT procurement policies. The code is written to encourage and pursue competition in all of the state's purchases, except in situations in which competition is nonexistent. In such cases, justifications are to be submitted and approved by the State Procurement Office (SPO). This process of approvals used to take a long time for each purchase. To address this, the Arizona Transportation Research Center (ATRC), a body within the department that is involved in evaluating products used by the department, implemented a process by which all justifications are submitted for approval by SPO as soon as a proprietary product is approved for use; then a contract is written and issued by ADOT Procurement for the purchase of these parts by any maintenance organization in the state.

Maintenance Products Evaluation Committee

ADOT has established several committees that review new products introduced by vendors. The Maintenance Products Evaluation Committee, administered through ATRC, is one of those committees and is composed of line maintenance and administrative personnel and at least one representative from Procurement. This committee reviews and approves products for use on the ADOT system. The product must meet standard construction specifications, standard plans, and applicable maintenance practices, and it must not require major retooling of maintenance equipment or processes. Materials approved by the other committees that relate to maintenance activities require approval by this committee before being included on the approved product list.

New Research Project on Procurement Process

On construction projects, new types of guardrail end treatments are often used. This reflects the ever-changing safety standards. However, maintenance sometimes cannot obtain replacement parts in a timely manner because of the proprietary nature of many of these parts and the present procurement process. It can take up to 6 months to obtain repair parts. This leaves a potentially dangerous situation in the field. Similar experiences are reported for road weather information system equipment repairs and for leading-edge pavement repair materials that often are proprietary.

The objective of this research is to establish improved procurement processes that better accommodate the needs of maintenance. The results of this research would be used to modify the current procurement process for maintenance activities.

The research efforts being pursued by ADOT reflect the continuing effort to provide maintenance personnel with more tools with which to perform their functions.

Holbrook Strategic Goal and Quality Process

As part of a larger strategic planning effort within ADOT, the Holbrook district established the goal of maintenance materials quality: establishing and implementing an ongoing program to train maintenance personnel in materials quality and testing along with ensuring that all materials used by maintenance forces meet specifications. The district's HEAT (Holbrook Employees Achieving Together) team was formed with a membership of materials testing personnel and line maintenance personnel. The initial process improvements proposed by the team include training of maintenance personnel in materials sampling and testing, and developing and testing an evaluation program of paving materials being used in the Holbrook district. The paving material that has the most impact on the program is asphalt concrete (AC) cold mix, which is made locally by some of the maintenance forces or purchased commercially.

The training program focuses primarily on educating all maintenance personnel in techniques for sampling and testing soils, aggregates, and asphaltic concrete. The education effort is concentrated in these areas because most maintenance employees should be involved in these materials-related functions. The course outline is given in Figure 1.

The program for evaluating the AC cold mix was based on the fact that much of the pavement work in the district requires cold mix, and approximately one-half of the maintenance materials budget is spent on cold mix. District maintenance forces have had to purchase more cold mix and mineral aggregate commercially and were not sure of the quality of the product they were getting. There also was the problem that some pavement patches failed because of poor-quality mix. The money and time spent and the impact the quality of AC cold mix had on the maintenance program made this an area the materials quality team wanted to address.

The test results of the materials sampled by maintenance indicate some initial major inconsistencies in their asphaltic cement content and in the aggregate gradations. Later samples show better consistency in both asphaltic cement content and aggregate gradations in the commercial mixes. The changes can be attributed to two factors. Since testing of the products began, the vendors have been making a greater effort to meet the specifications. The second factor is that since maintenance personnel have been trained in materials quality, they are making a greater effort to address the issue of quality materials. The actual test results for commercial mixes are given in Figure 2.

The test results for noncommercial mixes (Figure 3) show a greater variance in oil content and gradation. Much of this variance is attributed to maintenance personnel still doing things "the old way" instead of attempting to apply their new knowledge to an old situation. Another factor is that some of the mineral aggregate being used was not evaluated when delivered, and AC mix designs have not been developed for this material.

The correlation between the test results and the performance of the material is the area that is still being explored. The forms in Figure 4 are examples of what has been distributed to maintenance personnel. As can be seen in the figure, the results to date have been disappointing because of the lack of participation from district personnel, the lack of a scoring system to address the actual performance of the patch, and the continued need to educate personnel about the benefits of doing this evaluation.

Another measurement is tied to materials and workmanship quality and is also a component of the incentive

Maintenance Materials Training
Holbrook Lab
16 Hours Training
2 1/2 Days

Introduction

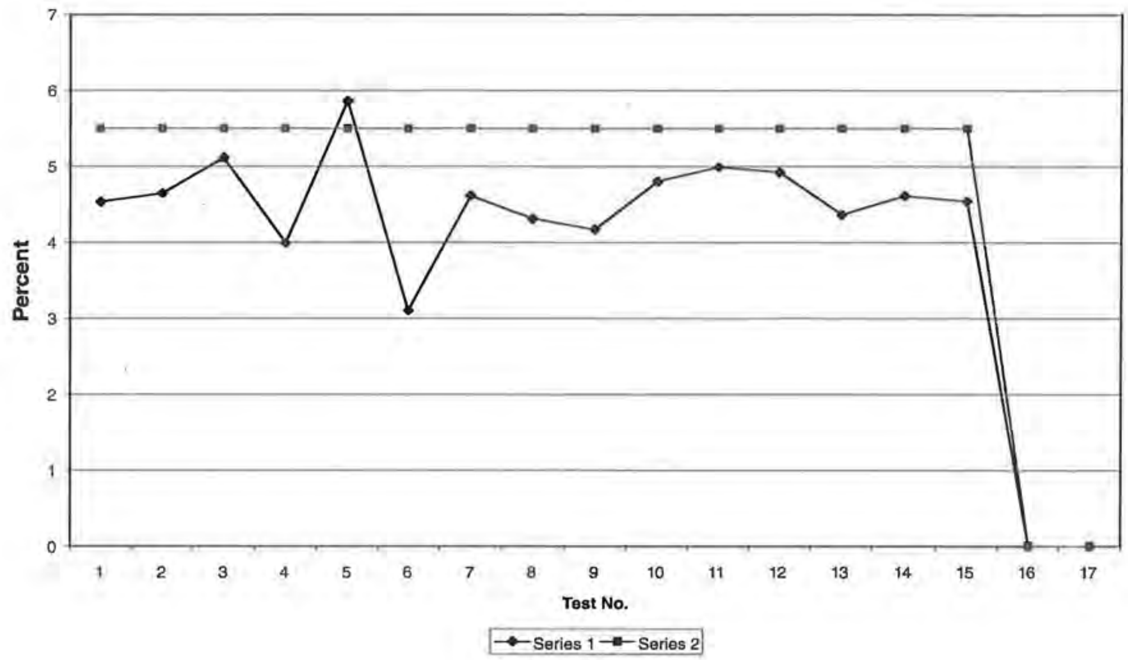
A. Purpose of the Seminar
1. Improve communications.
2. Provide useful tools and information.
3. Exchange ideas.
4. Aquaint Maintenance Personnel with Lab Tests.

B. Why is testing needed?
1. Testing tells you if you are getting the product you pay for.
2. Testing tells you "how much." It provides you with a way of measuring how much asphalt is in a mix, how much aggregate is in a windrow, etc.

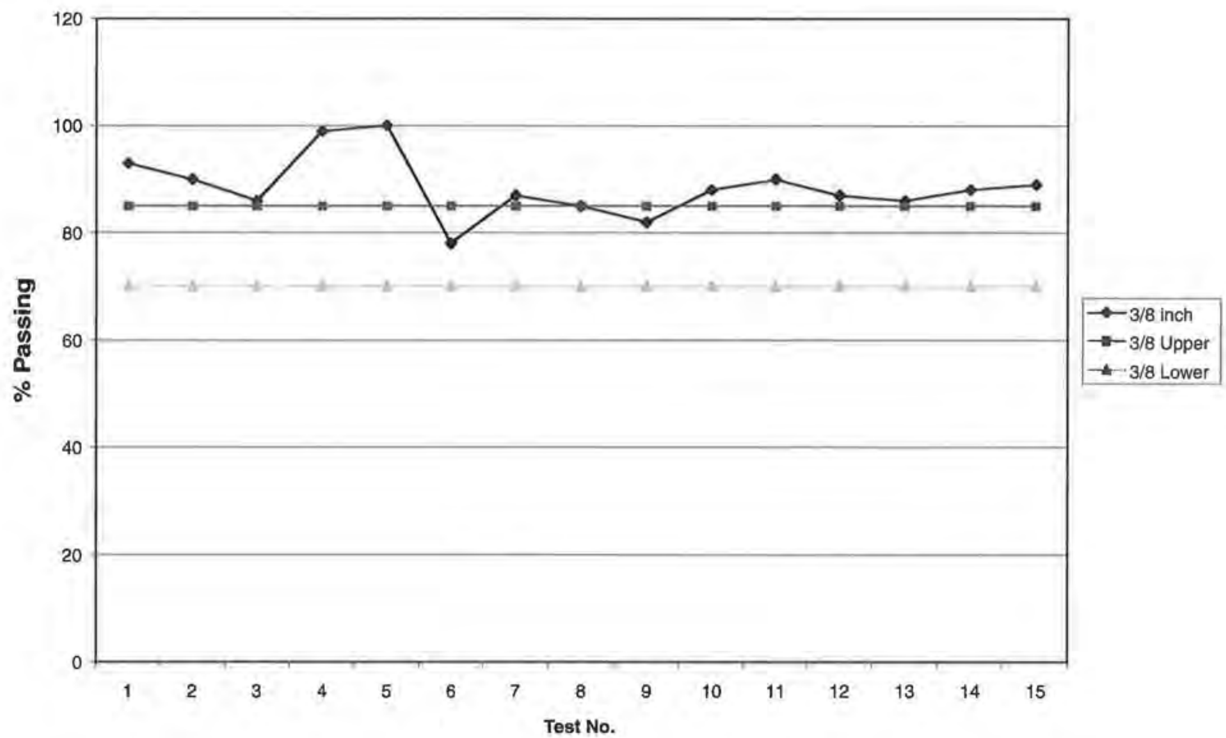
C. Summary of the Course
We will discuss Geology, Soils and Aggregates, Concrete, Asphalts, Asphalt Mixes, and Seal Coats, relating each of these materials to Maintenance uses.

Soils/Soil Classification/Soil Identification. Gradation and P.I.
Proctors/Max.Den., Opt. Moisture for Sandy Material. Clayish Material & Silt Material. Shows the curve as materials change weight due to percent moisture added.
Aggregates: Sampling Stockpiles, Unit Weight Calculations, Stockpile Calculations. Gradation.
Seal Coats: Chip Spread and Oil Spread Calculations.
Asphaltic Concrete: Asphalt mixing at a Hot Plant, laying Asphaltic Concrete with a Laydown Machine.
Asphaltic Concrete Testing: Showed the equipment use to get percent asphalt using the ignition oven.
Testing of Bituminous Mixtures with Marshall Apparatus. Bulk Density.
Maximum Theoretical Specific Gravity of Field Produced Bituminous Mixtures (Rice Test)
Gradation on Aggregates after the Asphalt is burned off.
Cold Mix: Mixing Cold Mix in a turntable, calculating the amount of aggregates in a windrow, to determine how much oil to add.

FIGURE 1 Maintenance materials course outline.

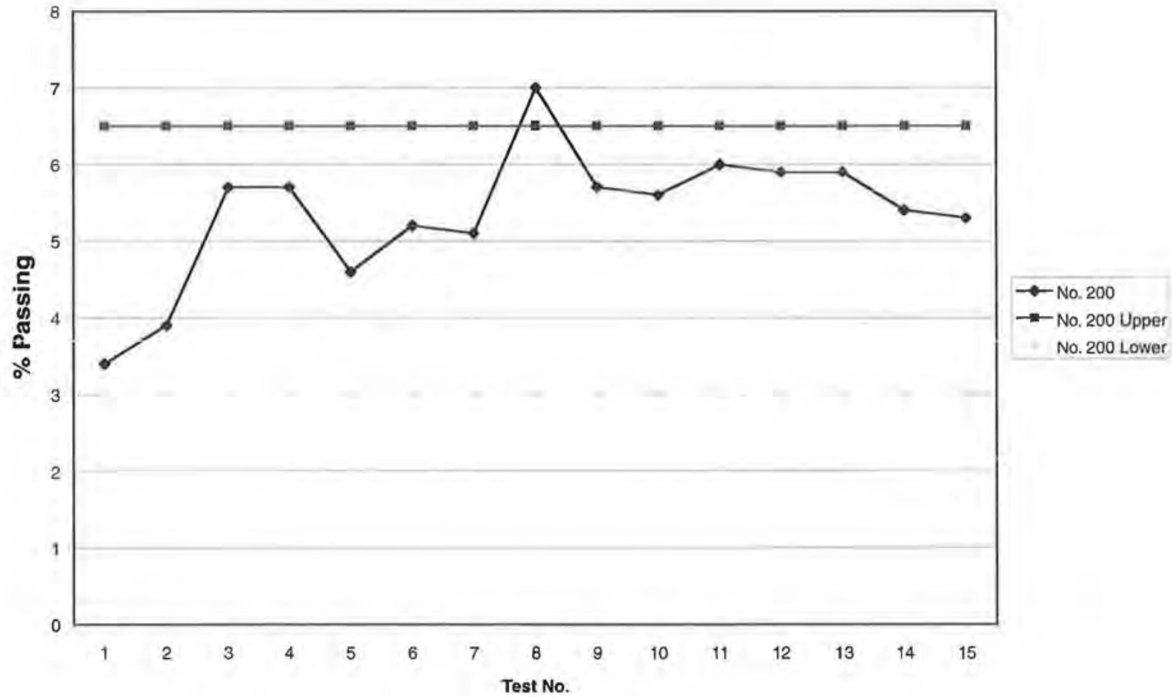


(a)

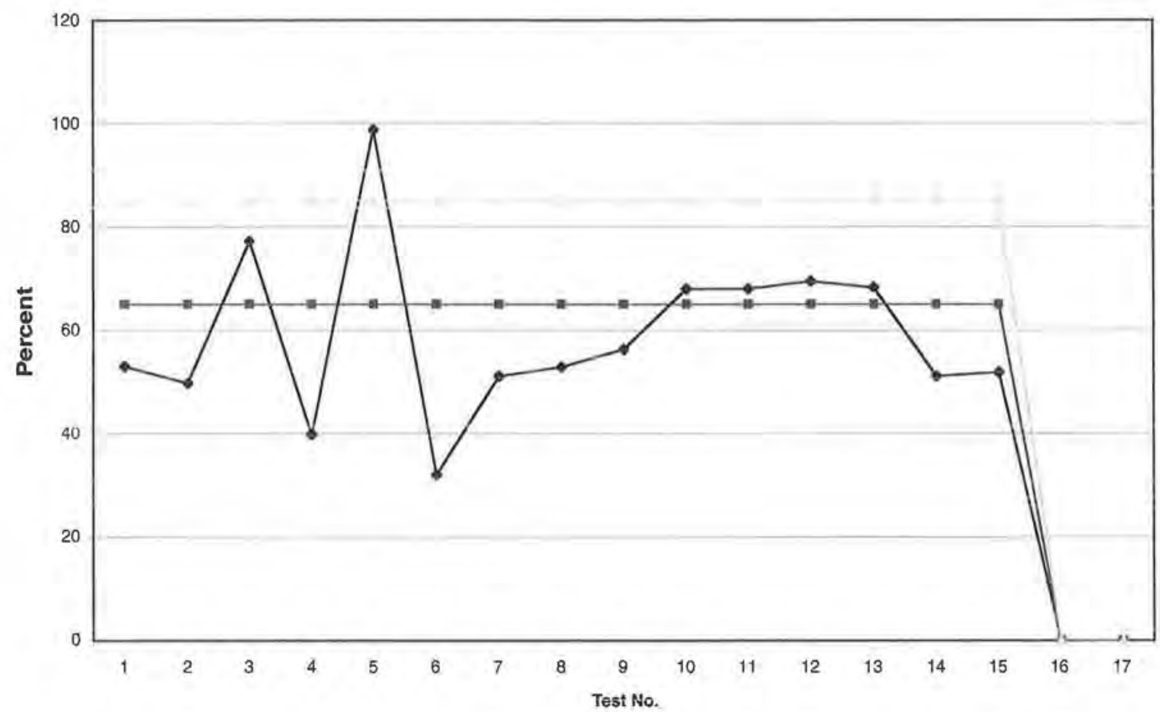


(b)

FIGURE 2 Test results for commercial mixes: (*a*) cold mix asphalt percent, (*b*) ⅜-in. gradation (1 in. = 25.4 mm). (*continued on next page*)

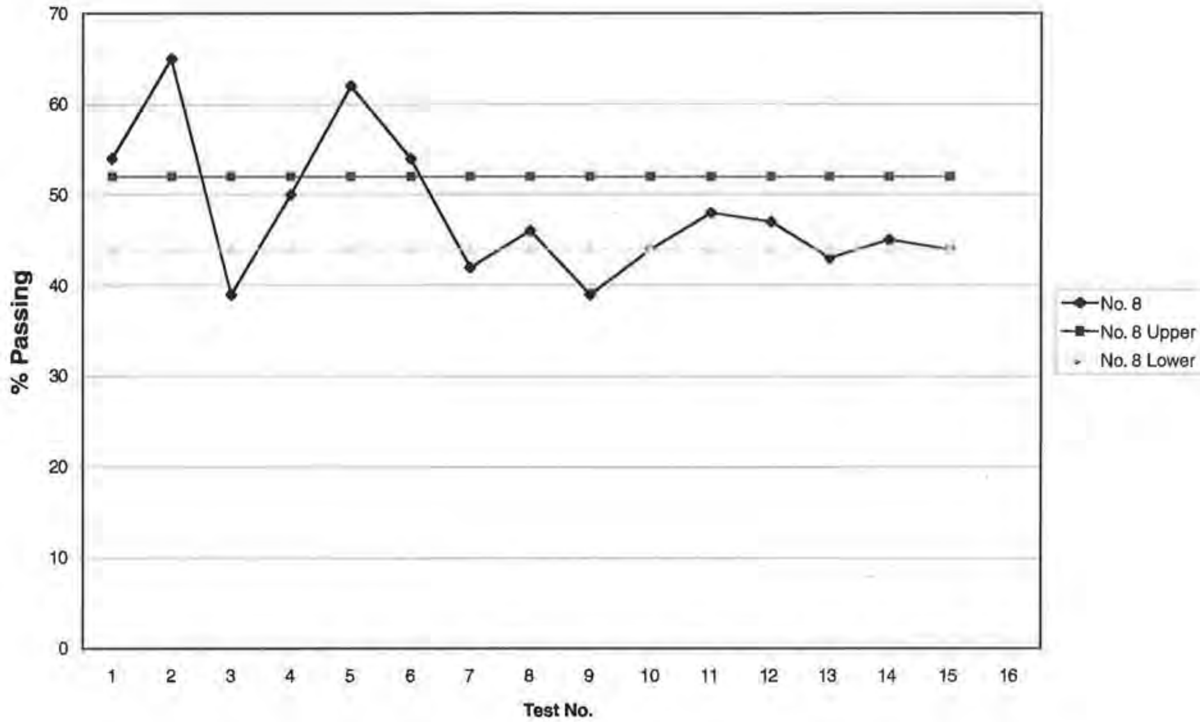


(c)



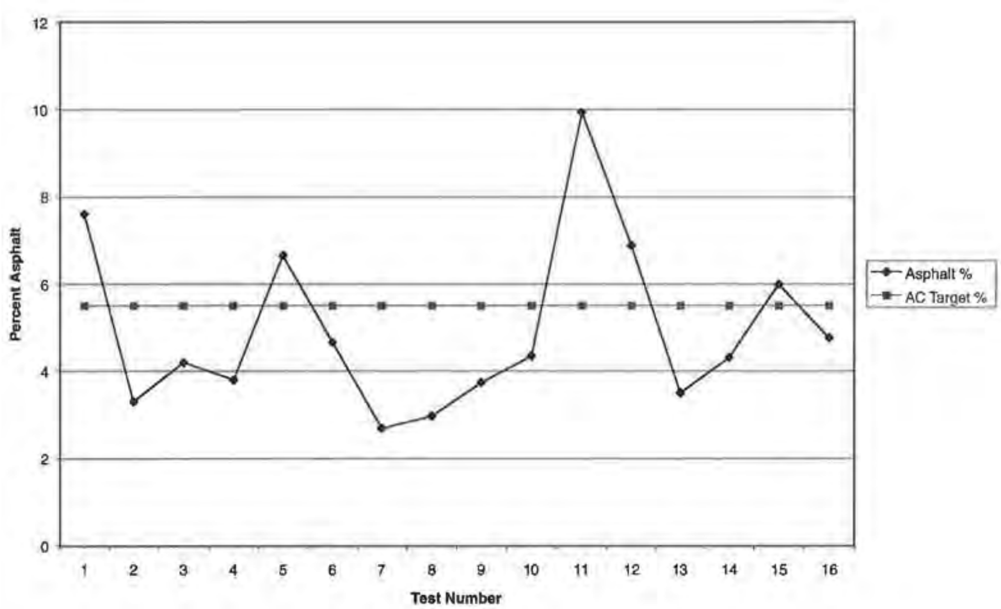
(d)

FIGURE 2 (*continued*) Test results for commercial mixes: (*c*) No. 200 gradation, (*d*) cold mix aeration percent. (*continued on next page*)



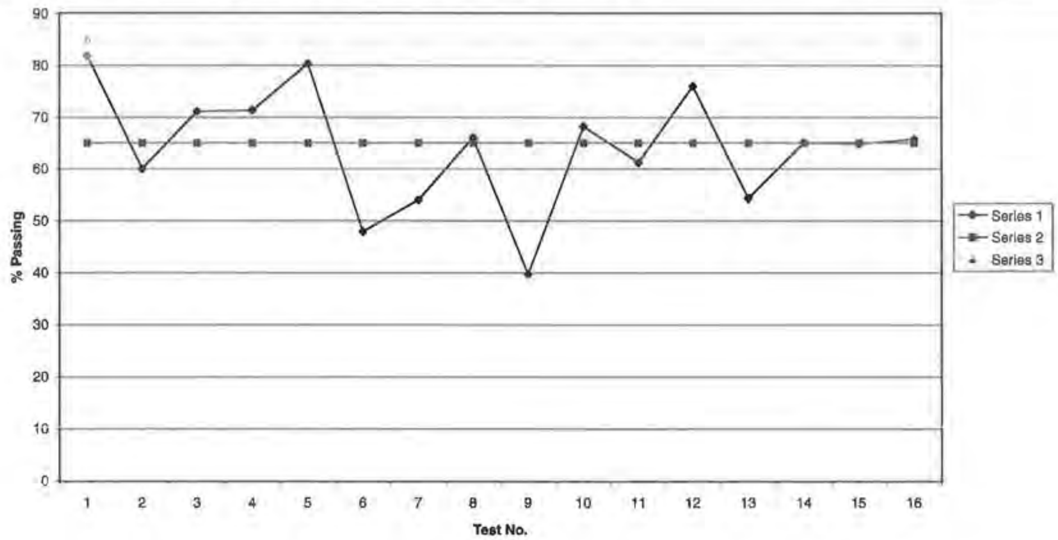
(e)

FIGURE 2 (*continued*) Test results for commercial mixes: (*e*) No. 8 gradation.

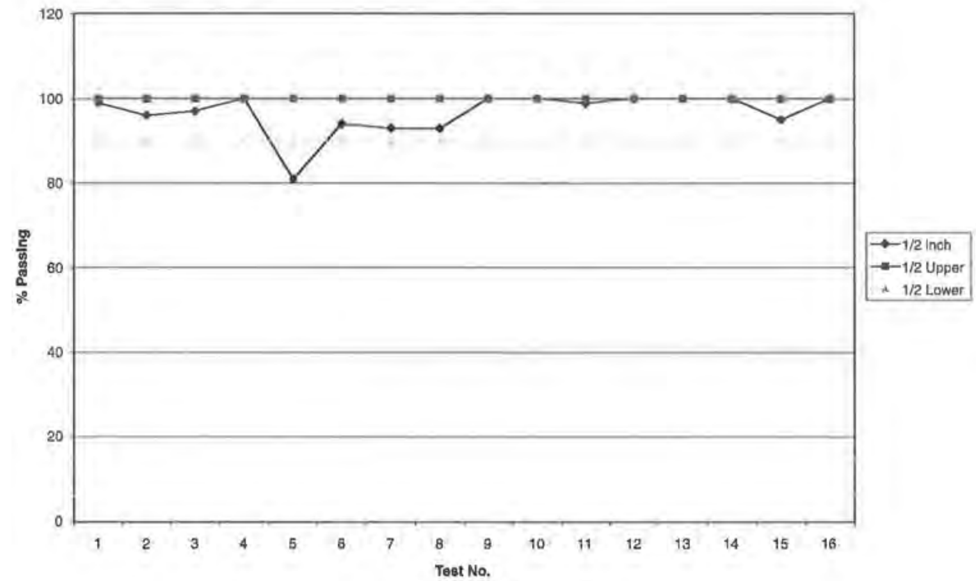


(a)

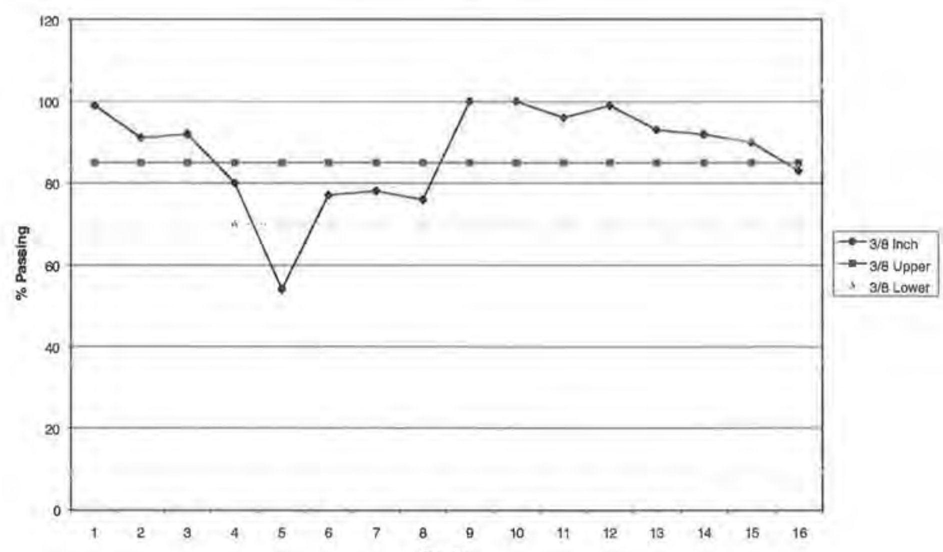
FIGURE 3 Test results for in-house mixes: (*a*) asphalt content. (*continued on next page*)



(b)

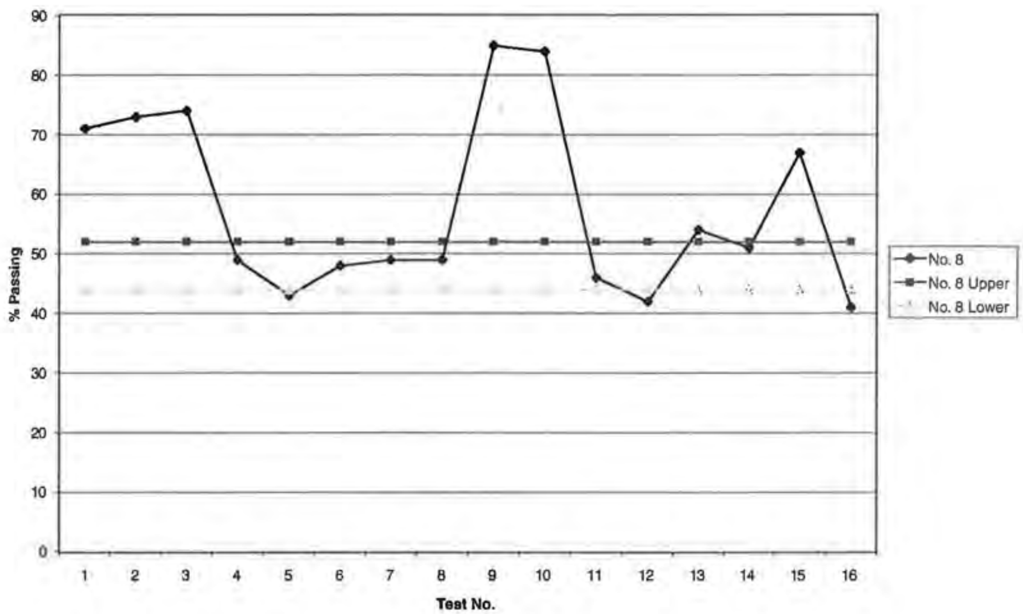


(c)

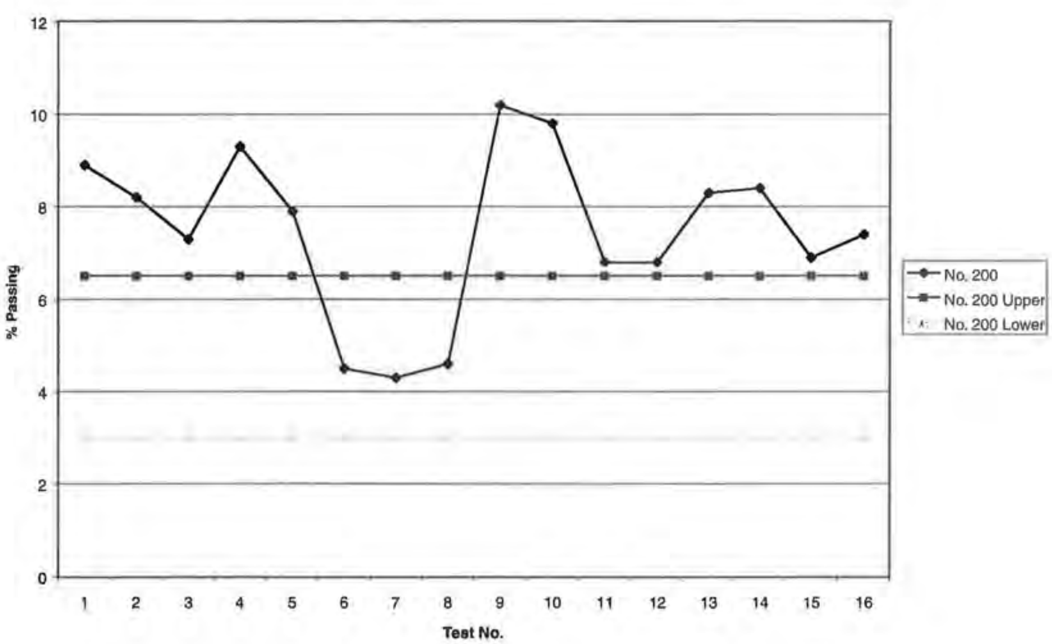


(d)

FIGURE 3 (*continued*) Test results for in-house mixes: (*b*) aeration, (*c*) ½-in. gradation, (*d*) ⅜-in. gradation (1 in. = 25.4 mm). (*continued on next page*)



(e)



(f)

FIGURE 3 (*continued*) Test results for in-house mixes: (*e*) No. 8 gradation, (*f*) No. 200 gradation.

COLD MIX PLACEMENT						MEASUREMENT	
Date	Location	Weather	Cubic Yards Gallons	Type	Supplier	Date	Comments
7/27/99	160 366.4-366.5		44 100	AC Field Mix MC 250	Southwest Sand & Gravel Paramount	01-18-2000	Materials not staying its place.
7/29/99	160 360.6-360.8		29 150	AC Field Mix MC 250	Southwest Sand & Gravel Paramount	01-18-2000	Some are coming out.
7/30/99	160 360.6-360.7		35 100	AC Field Mix MC 250	Southwest Sand & Gravel Paramount	01-18-2000	Some are coming out
8/23/99	160 423.2-423.8		46 100	AC Field Mix MC 250	Southwest Sand & Gravel Paramount	01-18-2000	Some are coming out.
8/24/99	160 399.4-399.5		38 100	AC Field Mix MC 250	Southwest Sand & Gravel Paramount	01-18-2000	Most MATERIAL coming [illegible]
8/25/99	160 399.3-399.5		48 75	AC Field Mix MC 250	Southwest Sand & Gravel Paramount	01-18-2000	Materials is coming out.
8/26/99	163 399.3-401.9		53 100	AC Field Mix MC 250	Southwest Sand & Gravel Paramount	01-18-2000	MATERIALS is coming out.
9/20/99	163 413.2-413.7		35 150	AC Field Mix MC 250	Southwest Sand & Gravel Paramount	01-18-2000	We made level and some are coming out.
9/24/99	163 401.6-401.7		18 150	AC Field Mix MC 250	Southwest Sand & Gravel Paramount	01-18-2000	ok
9/27/99	160 459.5-459.6		40 150	AC Field Mix MC 250	Southwest Sand & Gravel Paramount	01-18-2000	Poor bounding due to material grade
9/28/99	160 463.4-463.6		48 80	AC Field Mix MC 250	Southwest Sand & Gravel Paramount	01-18-2000	Some leveling material coming out due to material grade.
10/6/99	160 462.5-463.2		36 100	AC Field Mix MC 250	Southwest Sand & Gravel Paramount	01-18-2000	Not bounding like it should be due to poor material grade.
10/7/99	160 463.4-463.5		28 75	AC Field Mix MC 250	Southwest Sand & Gravel Paramount	01-18-2000	Poor material grade coming out in spots.

MATERIALS that we use from Southwest Sand & Gravel are mostly sand and not enough gravel in it. We been get better materials from Jerry Holiday which we been using all these years.

COLD MIX PLACEMENT							MEASUREMENT	
DATE	LOCATION	WEATHER	CU YD/TON	TYPE	MADE BY ADOT	SUPPLIER	DATE	COMMENTS
6/3/99	I-40 EB F 347.6/348.0	Clear 90	10/CYD	OZA		B/H	6/7/99	TOP LAYER LOOSE [illegible]
6/7/99	I-40 WB 3214 323.0	Clear 92	140/CYD	OZA		BH	6/10/99	" "
6/9/99	I-40 WB 320.0/322.0	Clear 90	90/CYD	OZA		BH	6/10/99	" "
6/10/99	I-40 WB 320/322	Clear 90	35/CYD	OZA		BH	6/18/99	" "
6/11/99	I-40 324.0 325.0	Clear 91	50/CYD	OZA		BH	6/18/99	" "
6/17/99	I-40 EB 322.0 327.0	Cloudy [illegible]	35. CYD	OZA		BH	7/1/99	" "
6/18/99	I-40 WB 328.1 329.9	Partly Cloudy 89	50.0 CYD	OZA		BH	7/1/99	" "

FIGURE 4 Evaluation forms (1 yd^3 = 0.76 m^3; 1 gal = 3.8 L).

pay program for maintenance. This measurement is part of the quality measurement and the criteria for several activities. The criteria being used by those evaluating the quality of the mix and the workmanship of the crew are noted in Figure 5. The actual measurements for the leveling activity (Activity 102) are shown in Figure 6. This system could have greater possibilities in the long run because incentive pay for a maintenance section depends on quality results.

Discussion of Issues

In addressing the issue of procuring quality materials for maintenance and evaluating the performance of the material, several factors come into play. The first is specifying the material needed by maintenance. ADOT says that use of the construction specifications to designate the material for maintenance should be the standard. However, construction specifications are written assuming average conditions, adequate preparation of underlying conditions, and pricing based on mass production techniques, and assuming that the equipment available to contractors is not available for the smaller projects taken on by maintenance forces.

Another factor is local material variability and microclimates. Construction standard specifications limit certain activities because of climatic conditions, whereas maintenance activities have to be done under a variety of conditions with little regard to climatic conditions. Because construction projects involve larger quantities of material, contractors will choose material sources based on quantity along with quality and economics. Maintenance choices are limited because of the smaller quantities of material needed, and the limited quantities affect the economics. In many cases, maintenance forces buy materials from suppliers that may not be involved in the larger construction projects where quality control is crucial.

The third factor concerns the type of material testing that is required for maintenance materials. Testing technology and procedures may not reflect maintenance conditions. There are standard asphaltic concrete tests, but there are very few standardized tests for AC cold mix. Determination of the performance of different materials is by individual evaluation of condition of the roadway or

QUALITY MEASUREMENTS

To assure ourselves that quality is maintained in the work we are doing through incorporation of the incentive awards in highway maintenance, a quality measurement will be incorporated into the program.

This measurement will comprise 20% of the award for the month.

HOW WILL IT BE MEASURED AND WHO WILL PERFORM THE QUALITY MEASUREMENTS?

This is a three-fold evaluation system based on a random choice of a work activity using the attached Activity Scoring System.

1) From District Management on a monthly basis at least one activity per Org shall be evaluated.
2) From Org supervision on a weekly basis at least one activity shall be evaluated.
3) From the Org members on a weekly basis one activity shall be evaluated and discussed.
4) From the Signing and Striping Org, members on a monthly basis, one activity shall be evaluated and discussed.

(It is desirable that the three levels of evaluations are on the same work activity. This is not mandatory, just suggested.)

For each of the above separate measurements the scores will be averaged from the Activity Scoring System received and a monthly value earned.

For activity being scored, please fill out the following: Date, route and mile post.

INSTRUCTIONS FOR FILLING OUT THE MEASUREMENT FORM

STEP 1: Choose the appropriate activity being reviewed.
STEP 2: For activity being scored, please fill out the date, route and mile post in the space provided.
STEP 3: Scorer: Circle D for District, S for Supervisor or C for Crew in scorer area. Put your name under the activity being scored.
STEP 4: From the score column, circle the score that best fits the finished product. (To the right of the score number is the criteria for receiving that score.)
STEP 5: Turn in completed form to the Org Maintenance Secretary or the appropriate person.

MAINTENANCE INCENTIVE PROGRAM

ACTIVITIES SCORING SYSTEM Scale: 1-3 on all

SCORER = D (DISTRICT) S (SUPERVISOR) C (CREW)

Activity / Description 101 Patch with premix

ACTIVITY DATE________ ROUTE______ MP______ SCORER D S C

SCORE

3 1) Finished surface for levelness. 2) Square up & straighten edges. 3) Broom loose excess material. 4) Seal patch as needed. 5) Remove all excess material.

2 #1 & 2 accomplished.

1 #1 accomplished.

Name______________ INSPECTION DATE ________

COMMENT:

MAINTENANCE INCENTIVE PROGRAM

ACTIVITIES SCORING SYSTEM Scale: 1-3 on all

SCORER = D (DISTRICT) S (SUPERVISOR) C (CREW)

Activity / Description 102 Level with premix

ACTIVITY DATE________ ROUTE______ MP______ SCORER D S C

SCORE

3 1) Taper new material to match existing. 2) Make sure surface is level. 3) Material stays on road. 4) No bleeding areas. 5) Sweep area. 6) Temporary centerline/lane striping. 7) Clean work area.

2 #1, 2 & 6 accomplished.

1 #1 & 2 accomplished

Name______________ INSPECTION DATE ________

COMMENT:

FIGURE 5 Incentive pay measurements. (*continued on next page*)

MAINTENANCE INCENTIVE PROGRAM

ACTIVITIES SCORING SYSTEM Scale: 1-3 on all

SCORER = D (DISTRICT) S (SUPERVISOR) C (CREW)

Activity / Description 105 Replace surface/base

ACTIVITY DATE ______ ROUTE______ MP______ SCORER D S C

SCORE

3 1) Finish surface for levelness. 2) Square up area. 3) Shoulder sloped as needed. 4) Temporary centerline/lane striping. 5) Remove all excess material.

2 #1, 2 & 4 accomplished.

1 #1 & 2 accomplished

Name____________________ INSPECTION DATE ____________

COMMENT: ______________________________

MAINTENANCE INCENTIVE PROGRAM

ACTIVITIES SCORING SYSTEM Scale: 1-3 on all

SCORER = D (DISTRICT) S (SUPERVISOR) C (CREW)

Activity / Description 112 Tight Blading

Activity date______Route__________ MP__________ Scorer D S C

SCORE

3 1) Sweep surface area first. 2) Apply tack coat. 3) Make sure premix surface is level and that new material is feathered to match existing pavement. 4) Roll material. 5) Install temporary centerline and lane striping. 6) Set up signs that read "LOOSE GRAVEL & FRESH OIL" with warning lights after work is completed.

2 #1, 2, 3 & 4 accomplished

1 Only _2_ of the _6_ accomplished

Name____________________ INSPECTION DATE ____________

COMMENT:

FIGURE 5 ***(continued)*** **Incentive pay measurements.**

the material and has very little to do with statistical information, which is available for determining the construction material specifications and testing.

The final factor is that there are no standard specifications that fit most maintenance needs. In some cases, the construction standard specifications do not exist for maintenance actions, and in some cases the specifications that are available are so generic that performance would be in question. Maintenance material needs may be similar to construction material needs, but there are different circumstances that would require further examination to determine the actual material usage quality.

The question is whether maintenance forces are getting the material that is needed and that will work under the existing conditions. Material specifications are critical in addressing this question. Personnel writing the specifications must be familiar with the products, the needs, and the material characteristics for a local area. The personnel best suited to determine the specifications are the local maintenance personnel. To ensure that local maintenance personnel could specify the needed material, additional training and educational efforts would be required, to provide the technical knowledge necessary to address the specification issue.

Another issue regarding specification is educating the procurement agent to what the local personnel need and how to write the bid documents so that the local issues are addressed. Many times the procurement agents are

ORG	ACTIVITY	DESCRIPTION	LOCATION	DATE	SCORE	REMARKS
8750	102	Level with Premix	I-40 - M.P. 288.1-288.2	08/18/1999	3	None Listed.
8751	102	Level with Premix	SR 99 - M.P. 39.0 - 41.0	07/07/1999	3	None Listed.
8751	102	Level with Premix	I-40W - M.P. 237.5-238.0	08/25/1999	3	None Listed.
8751	102	Level with Premix	I-40E - M.P. 237.3 - 238.0	09/20/1999	3	None Listed.
8751	102	Level with Premix	SR 87S - M.P. 353 -354	11/16/1999	3	None Listed.
8752	102	Level with Premix	US 160- M.P. 423.4-423.8	08/23/1999	3	Did not sweep. Wasn't necessary.
8752	102	Level with Premix	US 163- M.P. 413.2-413.6	09/20/1999	3	Excellent job. No waste, smooth surface
8752	102	Level with Premix	US 160- M.P. 462.5-463.2	10/06/1999	3	None listed.
8753	102	Level with Premix				No Activities scored for this duration.
8754	102	Level with Premix				No Activities scored for this duration.
8755	102	Level with Premix	I-40 - M.P. 320.4 - 321.8	07/14/1999	3	Curbing on guardrail needs sweeping.
	102	Level with Premix	I-40 - M.P. 312.3 - 312.7	11/12/1999	3	Shoulders need to be swept.

FIGURE 6 Quality measurements for Activity 102.

not fully aware of local conditions and material needs, and they generally will try to write bid documents based on their own experience or based on specifications that had been used before.

The results in Figures 2 and 3 demonstrate that there have been difficulties meeting specification and that the results in the field are showing that the current specification may not be performing well. The results show that the Holbrook district needs to address what material is being bought and made in-house and whether the existing material specifications should be changed.

After a contract is bid and awarded, the issue becomes ensuring that the quality of the material delivered is as originally specified. Continued emphasis on this phase is required, and it should have the same priority as construction materials testing. From the procurement side, there needs to be some flexibility in allowing the local personnel to administer the contract, including approving payments and rejecting noncompliance material. Again, there is an education factor that needs to be addressed for both the maintenance and the procurement personnel, so that they may understand the issues involved in administering contracts on a local level and according to local conditions.

Figure 7 gives an indication of how complex the interaction is among the quality of materials, specification of the materials, administration of the contract, and the working relationship of the maintenance and procurement personnel. The test results also indicate the complexity of getting what is needed.

CONCLUSIONS

An effort is needed to educate both procurement and maintenance personnel in specification writing, quality control, quality assurance testing, and identifying specific material needs. The specific educational focus for the maintenance personnel is determining the material required and then writing specifications to those requirements. Interpretations of test results and how they apply to particular situations need to be communicated to maintenance personnel as well.

It is also evident that contract management needs to be less centralized. Not only should there be an effort to educate procurement personnel about local conditions and needs, but the effort should include assigning greater responsibility to maintenance personnel for specifying material requirements. Developing and using a "one-size-fits-all" specification would not work in some areas. Along with the responsibility of specifying material, the maintenance personnel must be responsible for administer-

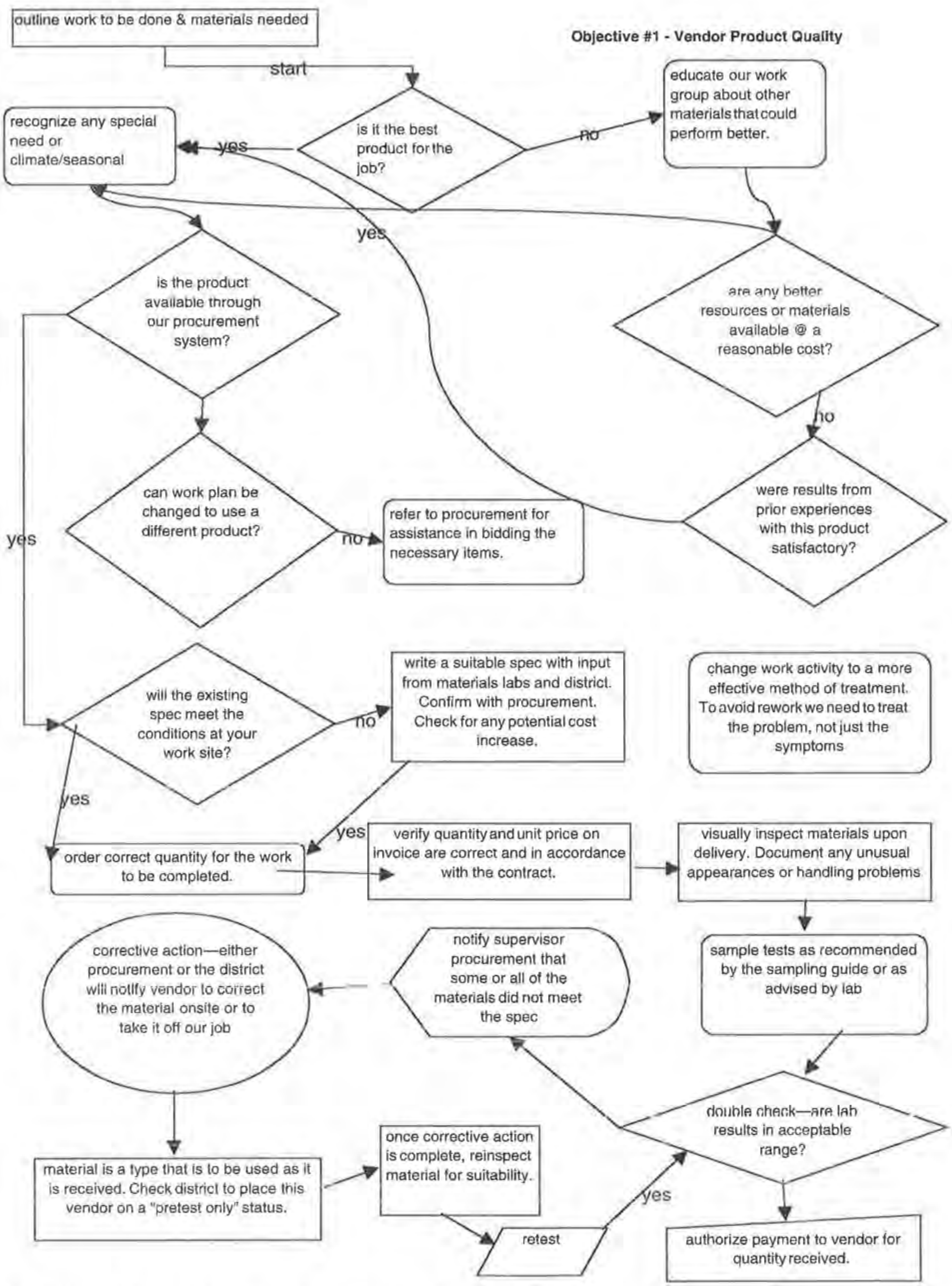


FIGURE 7 Holbrook district flowcharts. (*continued on next page*)

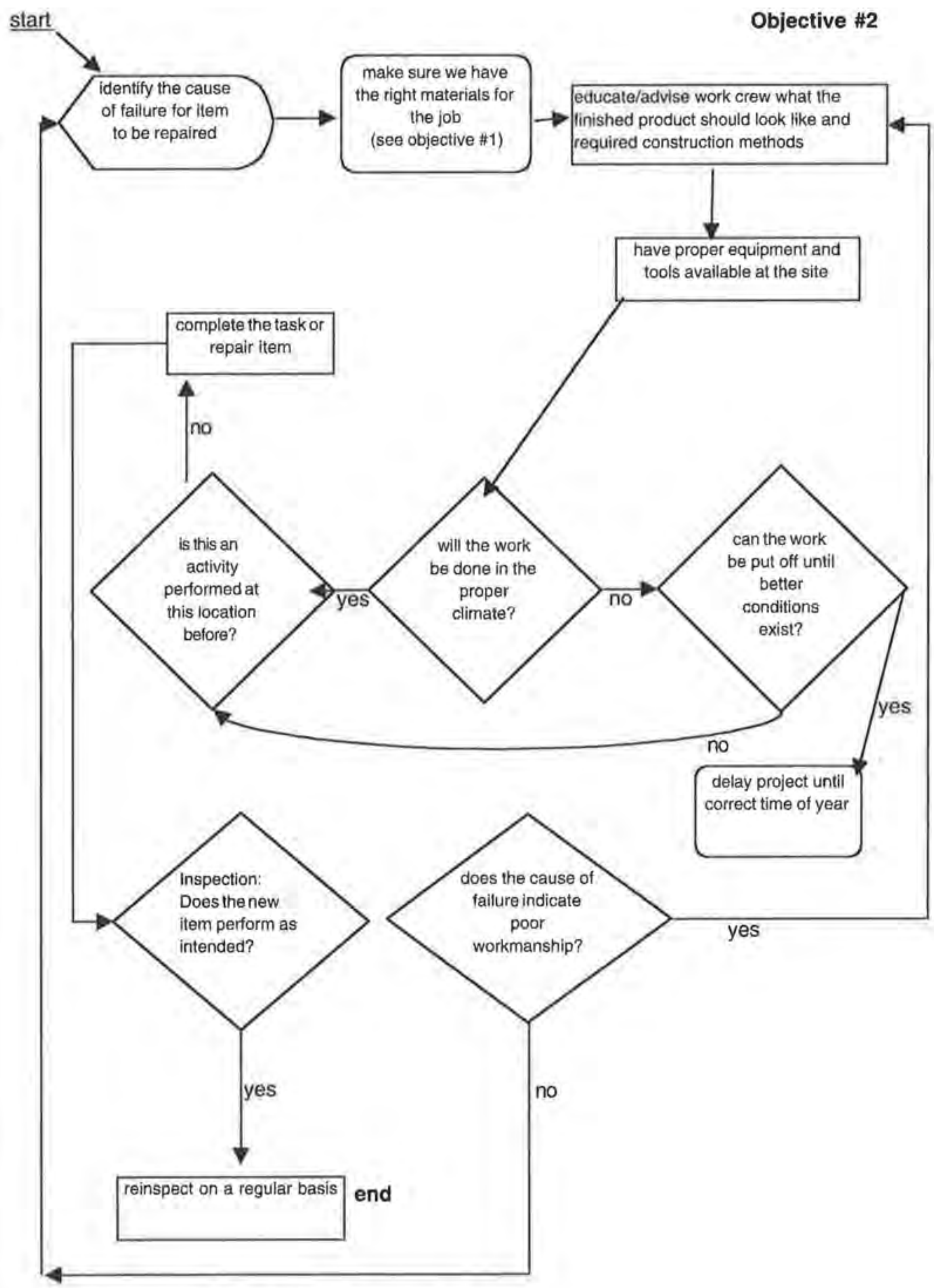


FIGURE 7 (*continued*) Holbrook district flowcharts.

ing the contract if material is being purchased. They are already responsible for in-house quality products, so they also should be responsible for ensuring that quality products are received from commercial suppliers.

An effort is needed to determine what quality control processes would be best for maintenance materials quality.

Future Research Needs

Future research is required to determine the level and amount of education for maintenance and procurement personnel in specification writing, quality control, quality assurance testing, and identifying specific material needs. Efforts are needed to define maintenance materials quality requirements and to determine whether changing the procurement process will result in maintenance personnel obtaining quality materials. Another facet of procuring maintenance materials includes the possibility of obtaining proprietary products and requiring a warranty on these products.

Maintenance materials quality may be similar to construction materials quality, but with the current constraints on obtaining maintenance materials, maintenance must be addressed on its own merits and needs.

Acknowledgments

The author acknowledges Al Zubi for contributions to the text on product resource investment, deployment, and evaluation; Joe Bailon for providing the material test results; Rob Middleton for creating the flowcharts; Patty Scott for scanning documents; Pat Anderson for helping consolidate the data; and all employees of the Holbrook district.

Part 4
BRIDGE MAINTENANCE

Evaluation of Penetrating Corrosion Inhibitor System

J. W. Bryant, Jr., R. E. Weyers, M. C. Brown, and R. M. Weyers

Sixteen reinforced slabs were cast with admixed chloride contents of 0.0, 0.35, 0.71, 1.4, 2.8, and 5.7 kg chloride per cubic meter of concrete. The slabs contained five isolated steel reinforcing bars with a 50-mm cover depth and were 1181 × 1067 × 216 mm. The slabs were stored at an outdoor exposure site in Blacksburg, Virginia, for 7 years before being treated with an alcohol-amine corrosion inhibitor. Treatments were three applications at a rate of 2.46 L/m^2 over the entire surface area or over a center strip that was perpendicular to the bar direction. The concrete mixture had a water-to-cement ratio of 0.45 and a 28-day compressive strength of 34.5 MPa. Corrosion assessment measurements before treatment included acid- and water-soluble chloride contents and corrosion potentials and rates. Corrosion potentials and rates were monitored for 1 year after treatment, and about 9 months after treatment the depth of inhibitor penetration was measured qualitatively (color indicator test) and quantitatively (parts per million). Results indicated that the inhibitor penetrated to the bar depth, but there was no significant difference in the corrosion potentials and rates between the treated and the untreated slabs or areas.

The process of chloride ion– and carbonation-induced corrosion of steel-reinforced concrete structures is well known. Methods to delay the process or extend the service life may be placed into two categories: those that delay corrosion deterioration of newly constructed structures and those that extend the service life of actively corroding structures. The design engineer may choose from numerous techniques for new structures, but there are a limited number of methods for existing structures undergoing corrosion deterioration. Methods applied to existing structures may be polymer impregnation, cathodic protection, electrochemical chloride removal, or realkalization and penetrating corrosion inhibitors.

Penetrating corrosion inhibitors may be separated into two categories, according to their penetrating mechanisms: immediate capillary absorption during application and subsequent gaseous diffusion through the empty, connective concrete capillaries; and capillary absorption at application and subsequent ionic diffusion through the saturated, connective concrete capillary system. Both systems may be referred to as posttreatment methods, with the formal corrosion inhibitors called migrating corrosion inhibitors.

Initial research was conducted on both posttreatment methods under SHRP C-103 (*1*). The corrosion inhibitor used for penetration by ionic diffusion was calcium nitrite, and the corrosion inhibitor used for penetration by gaseous diffusion belonged to the class of alcohol-amine compounds. Both corrosion inhibitors showed promise as posttreatment products (*2*). Corrosion-abatement performance assessments for the calcium nitrite field implementation trials conducted under SHRP C-103 are presented elsewhere (*3*). This paper presents the results of an alcohol-amine penetrating corrosion inhibitor. The research was performed subsequent to the

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SHRP C-103 research but used specimens cast during that program to determine the time to cracking following the initiation of chloride ion–induced corrosion of reinforcing steel.

RESEARCH PROGRAM

Specimens

Sixteen reinforced concrete slabs were cast in July 1990. The slabs contained five isolated steel reinforcing bars (see Figure 1). The slabs contained admixed chloride as sodium chloride, which ranged from 0.0 to 5.7 kg Cl^- per cubic meter of concrete (kg/m^3). The concrete was a typical bridge deck mixture with a water-to-cement ratio (w/c) of 0.45 and a 28-day compressive strength of 34.5 MPa. The slump range was 75 to 100 mm, and the air content range was 5.5 to 6.5 percent. The slabs, 1181 × 1067 × 215 mm, had a 50-mm concrete cover over the reinforcing steel.

Treatment

The slabs, which were stored outdoors in Blacksburg, Virginia, were about 7 years old when treated. The slabs, partially and fully treated, received three applications of an alcohol-amine penetrating corrosion inhibitor (APCI) at an application rate of 2.46 L/m^2. Table 1 presents the admixed acid- and water-soluble chloride contents and the treatment matrix. The APIC was applied to a 600-mm-wide center strip across the entire width of the slab and perpendicular to the five reinforcing steel bars. The APIC was applied to the entire surface of the fully treated slabs. The applications were in September 1998 following a relatively dry summer and at least 2 weeks after the last measurable rainfall.

Corrosion Assessment

Corrosion mitigation assessment testing consisted of ambient temperature, temperature at the bar depth, corrosion potentials, copper-copper sulfate halfcell (CSE), and corrosion current density, unguarded linear polarization device (3LP). The corrosion potential and corrosion current density readings were corrected to 20°C. In addition, the depth of the penetration of the APCI was measured by the APCI manufacturer both qualitatively (color test) and quantitatively as a function of depth from a 100-mm-diameter core from each admixed chloride series. The cores were drilled with a water-cooled diamond set drill bit.

For the full-treatment slabs, corrosion potentials and rates were measured at the center of each of the five steel reinforcing bars. For the partial-treatment slabs, the corrosion potentials and rates were measured along the centerline of the treatment strip and within both untreated zones at the interface line between the treated and untreated zones on each of the five steel reinforcing bars.

A set of corrosion assessment measurements were taken before treatment and then generally once a month after treatment for 1 year. The manufacturer's APIC measurements were conducted about 9 months after treatment and before the last two measurement periods. Measurements were made on each of the five bars at the same location throughout the 1-year assessment period. Results are presented as the average of the five measurements and the 95 percent confidence limits.

RESULTS

Figure 2 presents the ambient and concrete temperature at the reinforcing steel bar depth at each measurement period. As shown, the temperatures during the test period

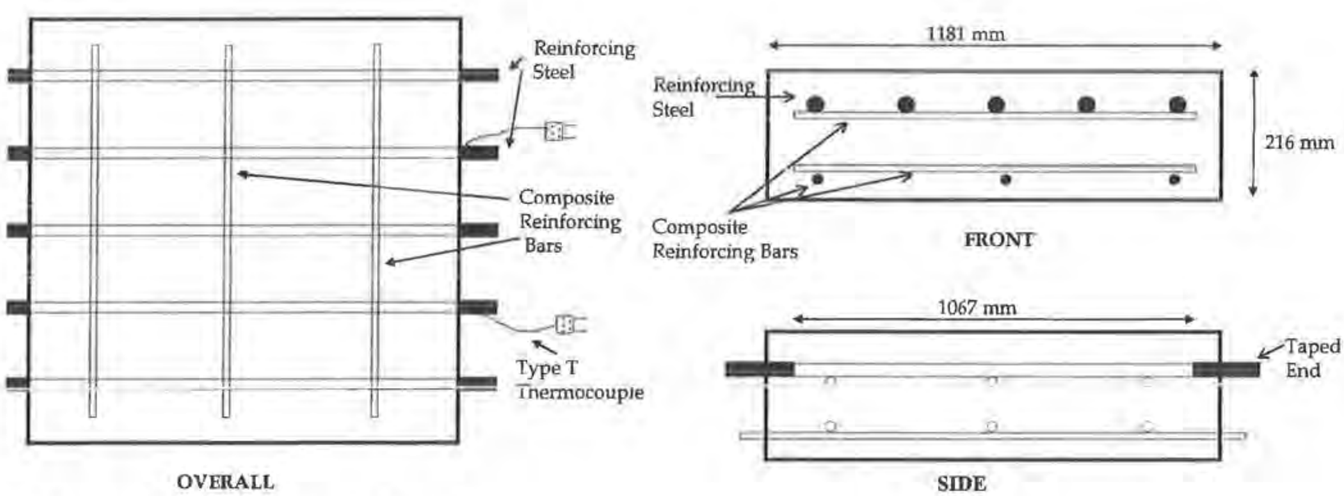

FIGURE 1 Reinforced concrete slab design.

TABLE 1 Posttreatment Test Matrix

	Admixed Chloride, kg/m^3					
	0.0	0.35	0.71	1.4	2.8	5.7
Measured Cl						
Acid Soluble	0.00	0.20	0.54	1.4	2.7	5.5
Water Soluble	0.00	0.19	0.50	1.3	2.5	5.1
Treatment						
None	1	1	1	1	1	1
Partial	0	1	1	1	1	0
Full	1	1	1	1	1	1

were somewhat variable and the concrete temperature generally was less than the ambient temperature. The concrete temperatures varied from a high of about 28°C during the summer months to a low of about 7°C during the winter months.

Figures 3 and 4, 5 and 6, 7 and 8, and 9 and 10 present the corrosion potential and rates for the fully treated and untreated slabs for the 0.00, 2.88, and 5.76 kg/m^3 series, respectively. Admixed series 0.36, 0.72, and 1.44 kg/m^3 are not presented because these relatively low admixed chloride content series are very similar to the control series of 0.00 kg/m^3.

Control Zero Admixed Chloride, Full Treatment

As shown in Figure 3, the corrosion potentials for the control zero admixed chloride full-treatment test were generally positive throughout the test period for both the treated and the untreated zero admixed chloride slabs. Also, there is no significant difference between the treated and the untreated slabs. Thus, the APCI appears to have no influence on the corrosion potential measurements, and these slabs show a very low probability of active corrosion.

The corrosion rates were the same for both slabs before treatment. After treatment, the corrosion rates for the treated slab were significantly greater for all measurement periods except the last, about 1 year after treatment. However, in the author's experience, the corrosion rate values presented in Figure 4 would be indicative of very little active corrosion. Also, it must be pointed out that the formation of the passive layer on steel in concrete is a continuous but diminishing process with embedment time.

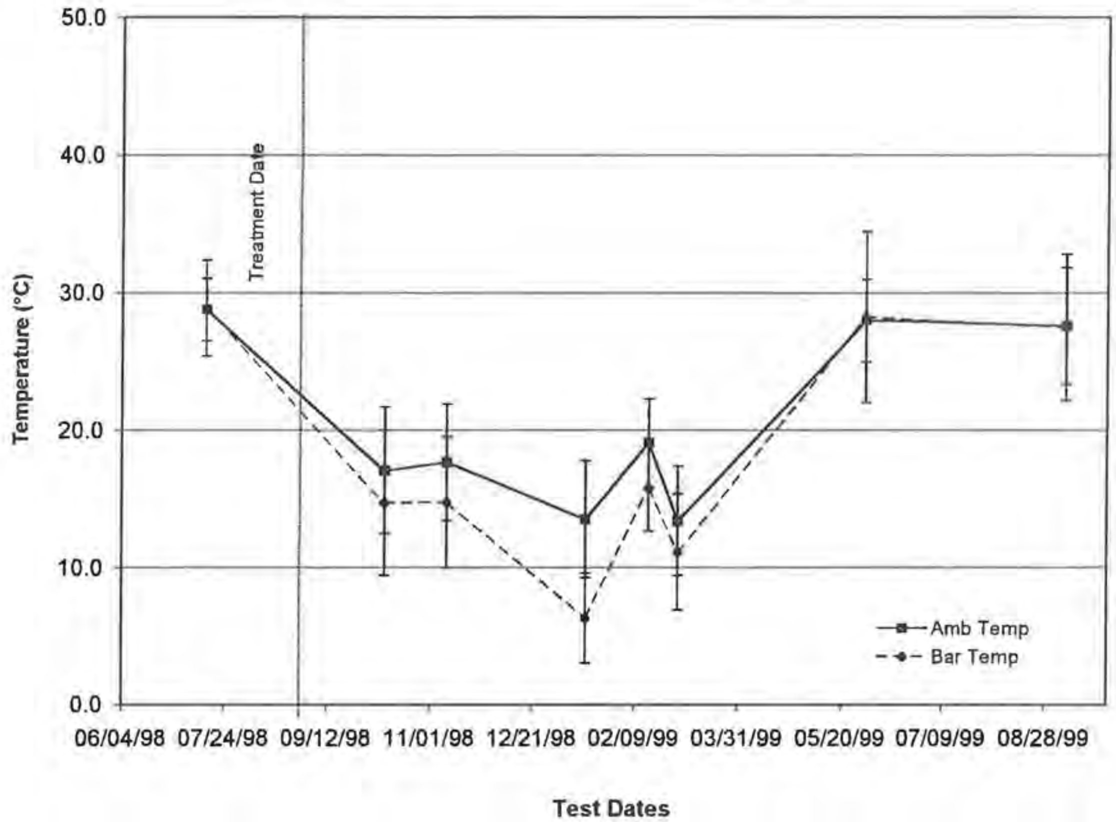

FIGURE 2 Average and 95 percent confidence limits of ambient and concrete temperature at bar depth.

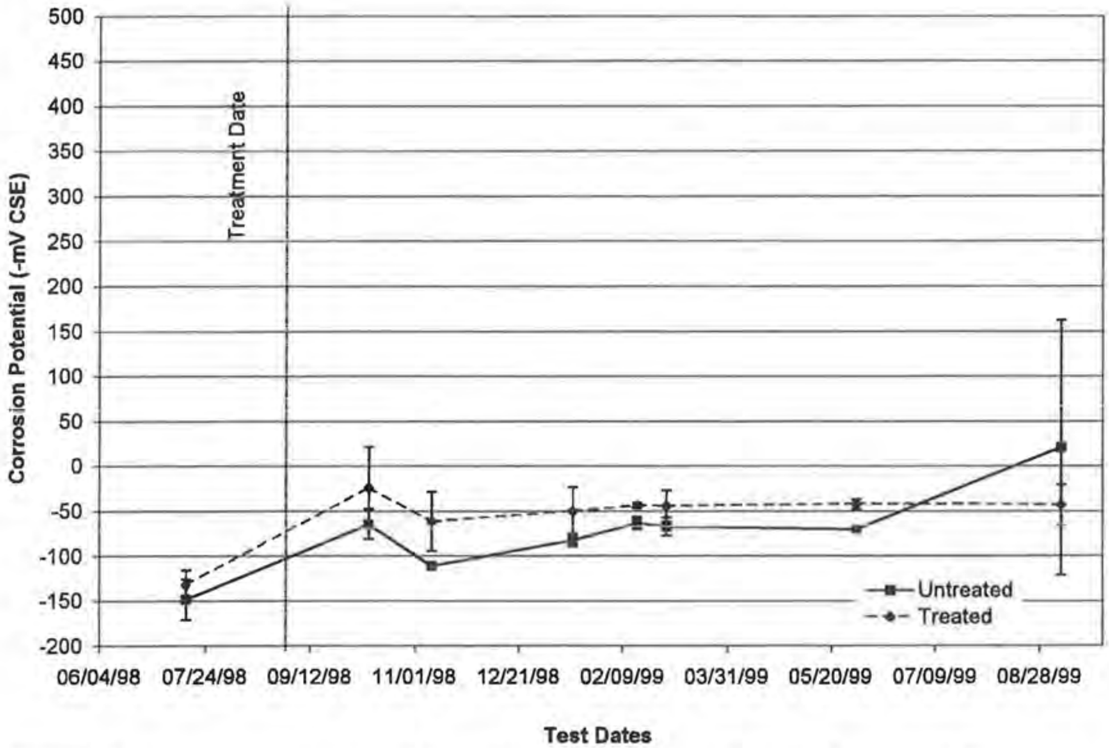

FIGURE 3 Average corrosion potentials and 95 percent confidence limits for the control full treatment series of zero admixed chlorides.

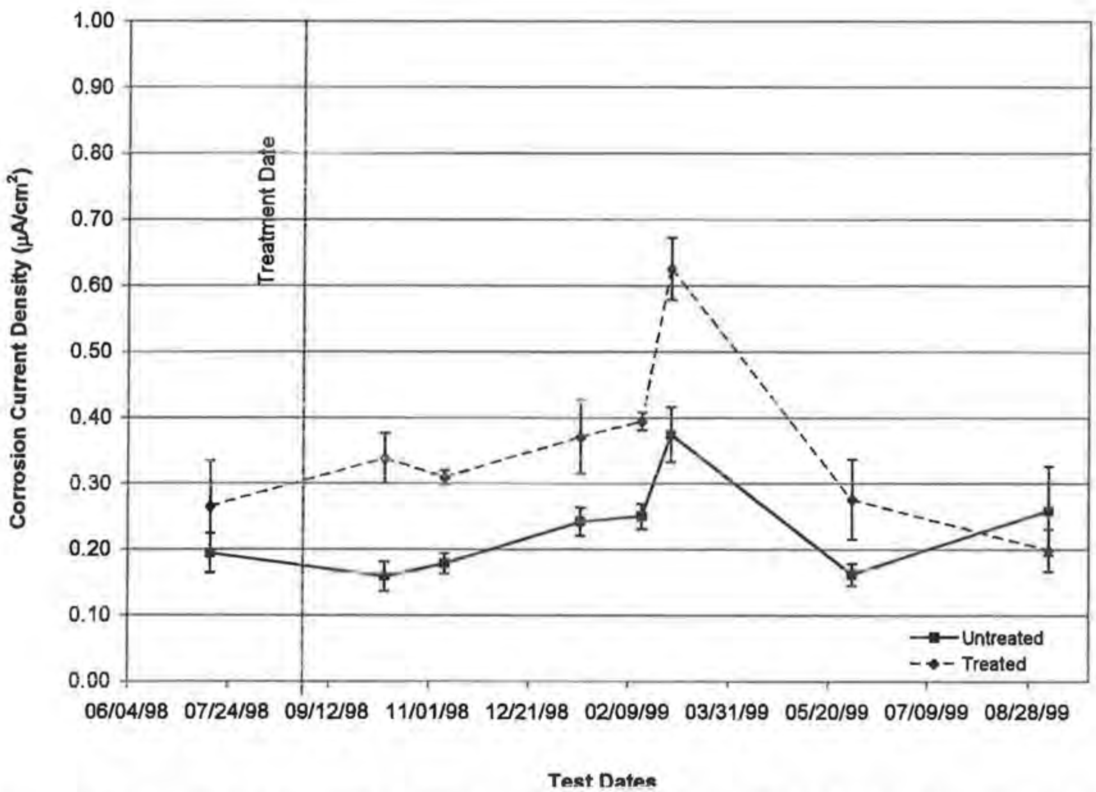

FIGURE 4 Average 3LP corrosion current density and 95 percent confidence limits for the control full treatment series of zero admixed chlorides.

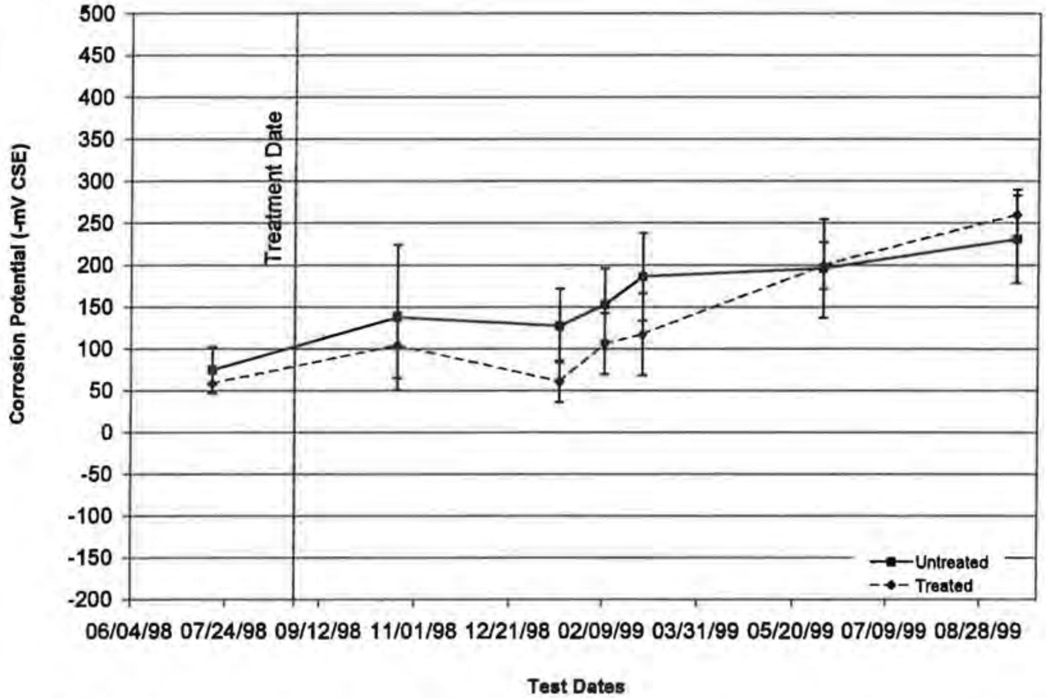

FIGURE 5 Average corrosion potentials and 95 percent confidence limits for the 2.88 kg chloride admixed full treatment series.

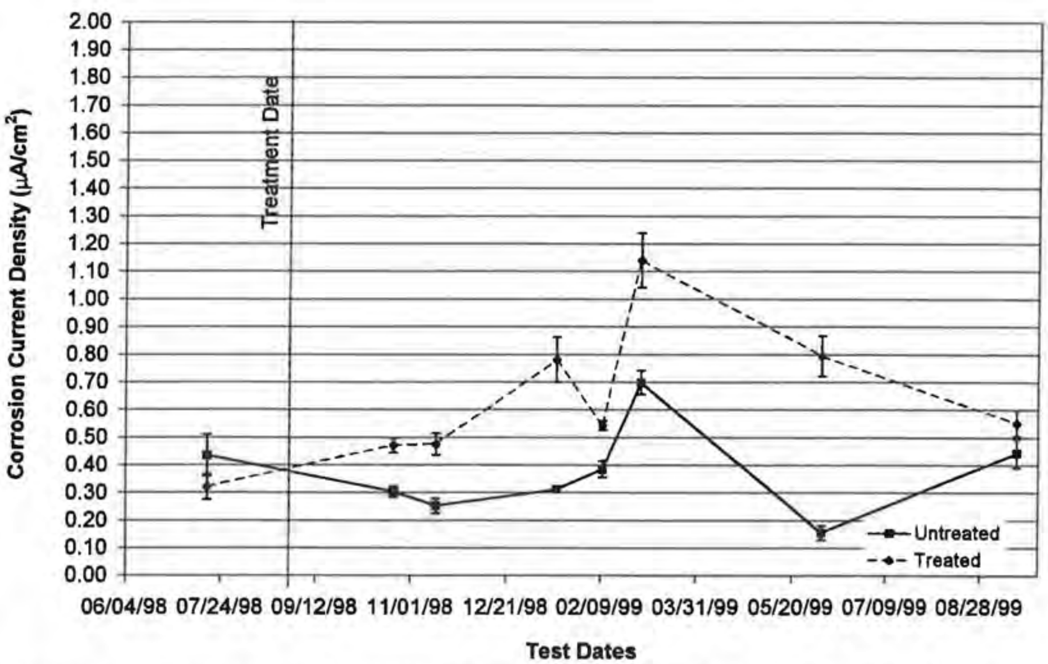

FIGURE 6 Average corrosion current density and 95 percent confidence limits for the 2.88 kg chloride admixed full treatment series.

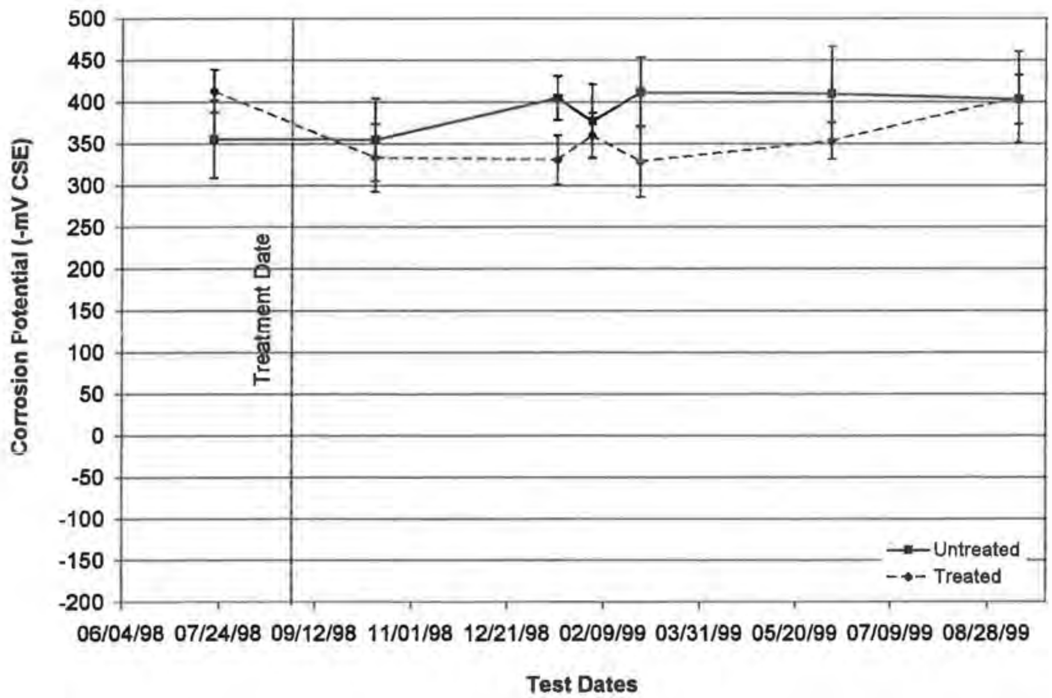

FIGURE 7 Average corrosion potentials and 95 percent confidence limits for the 5.76 kg chloride admixed full treatment series.

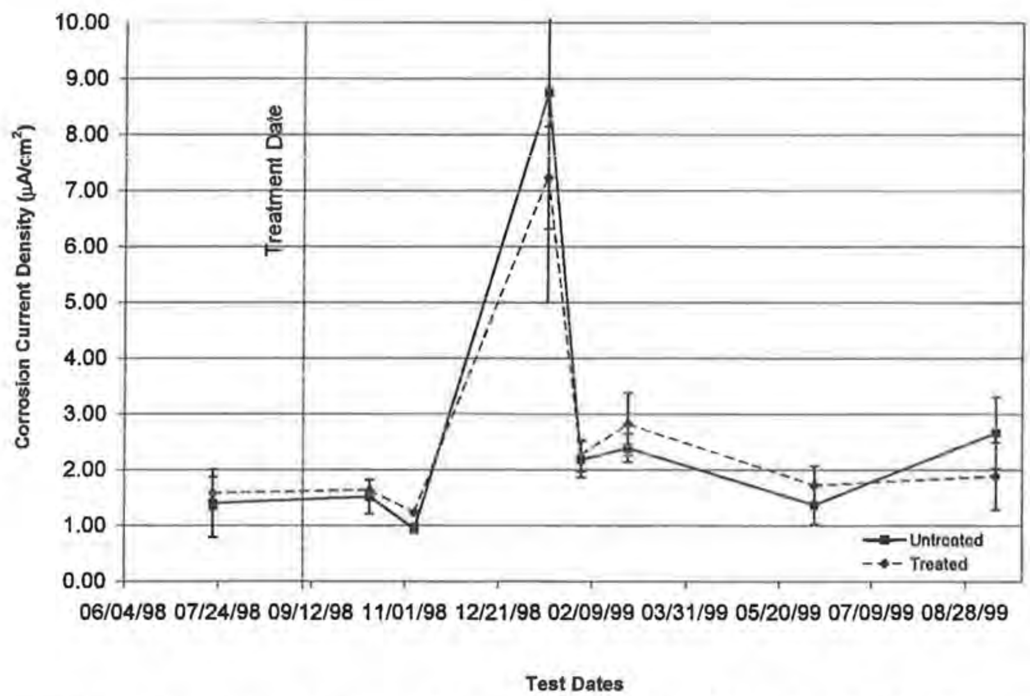

FIGURE 8 Average corrosion current density and 95 percent confidence limits for the 5.76 kg chloride admixed full treatment series.

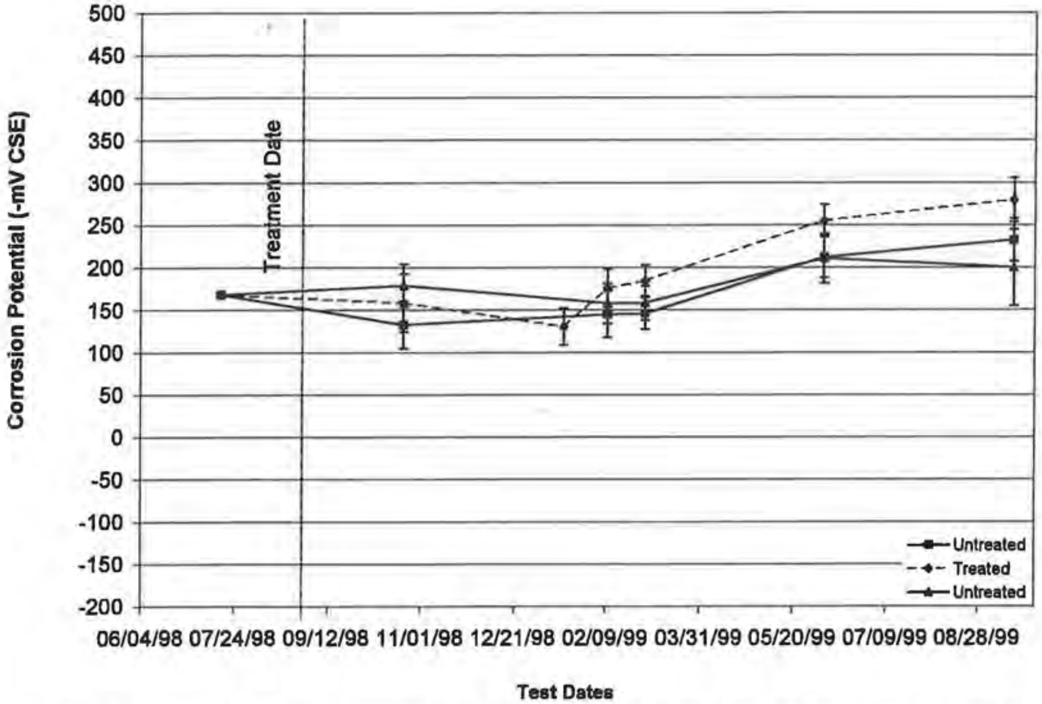

FIGURE 9 Average corrosion potentials and 95 percent confidence limits for the 2.88 kg chloride admixed partial treatment series.

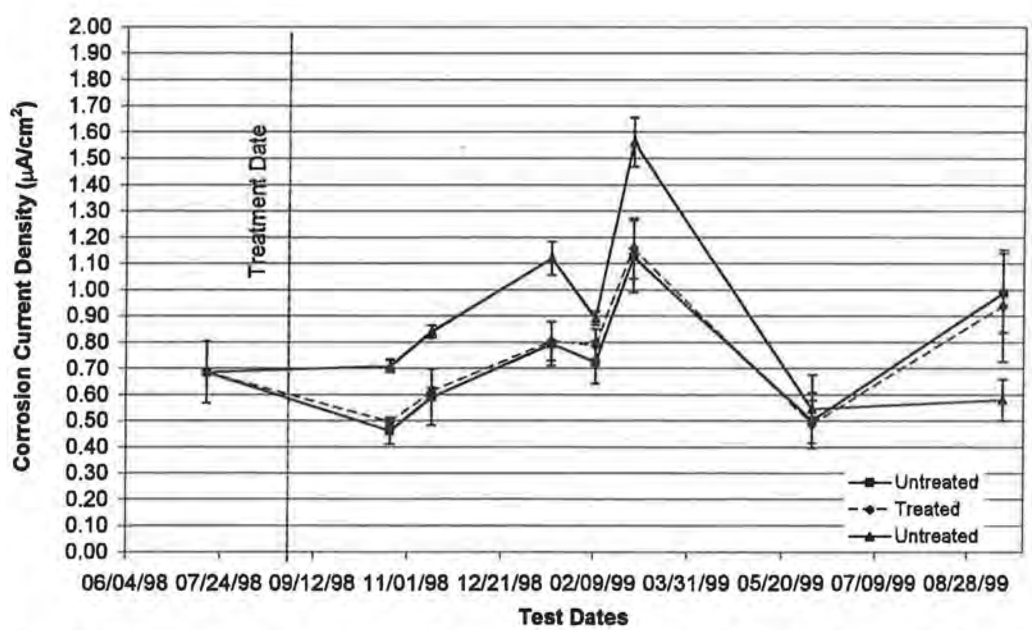

FIGURE 10 Average corrosion current density and 95 percent confidence limits for the 2.88 kg chloride admixed partial treatment series.

2.88 kg Series, Full Treatment

As shown in Figure 5, the corrosion potentials for the full-treatment 2.88 kg series were the same before treatment and throughout the 1-year assessment period. In general, the treated slab potentials were less negative than those for the untreated slab. The potentials become more negative throughout the test period, averaging about −60 mV CSE before treatment and about −200 mV CSE after 1 year. Accepted interpretation of these low negative values is that there is a less than 90 percent probability of active corrosion.

The corrosion rates for the 2.88 kg/m^3 series were the same before treatment; see Figure 6. After treatment, the corrosion rates were significantly higher for all measurement periods except at the 1-year period. The corrosion rates for this series are greater and are indicative of active corrosion conditions although the corrosion potentials are relatively low negative values.

5.76 kg Series, Full Treatment

The corrosion potentials before full treatment for the 5.76 kg series and throughout the assessment period of 1 year after treatment were generally more negative than the 90 percent probability of active corrosion value of −350 mV CSE; see Figure 7. There was no significant difference between the treated and the untreated slab potentials before and after treatment.

As shown in Figure 8, the corrosion rates were more active and ranged between 1 and 3 $\mu A/cm^2$ throughout the test period, except for large spiked measurement of about 8 $\mu A/cm^2$ at about 6 months after treatment. The corrosion rate values indicate moderate active corrosion condition, 1 to 3 $\mu A/cm^2$, and highly active corrosion at 8 $\mu A/cm^2$. There is no significant difference between the corrosion rate before or after treatment.

2.88 kg Series, Partial Treatment

The measurements for the partial-treatment slabs with 2.88 kg chloride were taken at the center of the treatment strip and along both interface lines between treated and untreated zones. Figures 9 and 10 present the corrosion potentials and rates for these conditions. As shown, the results are very similar to those for the fully treated series (see Figures 5 and 6). Thus, there appears to be no significant difference between the untreated and the treated sections and no reduction in corrosion activity.

Discussion of Results

For these APCIs to extend the service life of structures undergoing active chloride induced corrosion, they must

- Penetrate the cover concrete to depth of the reinforcing steel;
- Penetrate accumulated corrosion products in pitting cells to the depth where oxidation of the iron is occurring, or retard or stop the cathode reaction; and
- Inhibit active chloride induced corrosion cells in the presence of relatively high chloride concentrations.

To determine if the APCI penetrated the cover concrete, the manufacturer's representative conducted a qualitative color test and quantitatively determine the presence of the APCI in the cover concrete. The representative was first given a blind test with cores taken from treated and untreated slabs. The results of this blind test demonstrated that the color test could differentiate between the treated and untreated slabs. Subsequent tests were conducted on four cores, one each from the 0.36, 1.44, 2.88, and 5.76 kg/m^3 series. Table 2 presents the results of the color and measured APCI concentrations.

As shown in Table 2, the color test showed a presence of the APCI in the concrete at all five depths for the four cores except for the 51- to 63-mm depth of the 2.88 kg admixed chloride series core. The concentration of the APCI deceased rapidly from the 13-mm depth to the 13- to 25-mm depth and continued to decrease with depth. At the depth of the reinforcing steel, the concentration of the APCI was less than 13 parts per million for three of the cores and was not detected in one of the cores. Thus it appears that the APCI did penetrate the concrete to the depth of the reinforcing steel. Also, there appears to be some relationship between color intensity and concentration. Per the manufacturer's representative, if the color test

TABLE 2 APCI Color Test and Concentration

	0.35		1.4		2.8		5.7			
Depth mm	Color Intensity	Concen. ppm	Color Intensity	Concen. ppm	Color Intensity	Concen. ppm	Color Intensity	Concen. ppm	Color Intensity	PPM
0-13	S	1813	VS	650	S	1743	VS	1743	VS	650, 1097
13-25	M	338	S	113	S	391	S	391	S	1813, 113, 44, 312, 1743, 391
25-38	M	208	S	44	M	149	M	149	M	338, 208, <13, 95, 149
38-51	W	70	M	<13	VW	34	W	34	W	70, <13, 51, 26
51-63	VW	<13	W	<13	ND	<13	W	<13	VW	<13, 34

Note: VS: Very Strong; S: Strong; M: Moderate; W: Weak; VW: Very Weak; ND: Not Detected detects the presence of the APCI at a very weak level, the concentration is sufficient to be an effective corrosion inhibitor. Also, it has been reported that this APCI should have penetrated to a depth of 80 mm in 28 days at the lowest penetration rate and that the APCI is effective for chloride contents up to 2 percent by weight of cement (*4*). For this case, the highest chloride content of 5.7 kg/m^3 was less than 2 percent by weight of cement (377 kg/m^3) or 7.5 kg/m^3 concrete. Thus, the APCI should have demonstrated a reduction in active corrosion of the test period for the reported test conditions. However, the APCI did not show any reduction in active corrosion of these test conditions over the 1-year test period.

Questions remain. Was the APCI chemically adsorbed on the steel surface? What concentration on the steel surface is needed to reduce or stop corrosion? Also, at what APCI/chloride ratio is the inhibitor effective? It should be pointed out that the APCI concentrations were measured in the concrete. Thus, is the APCI primarily absorbed on hardened cement surfaces rather than the corroding steel surface, and does the color test measure the active corrosion inhibitor or some other chemical compound in the inhibitor?

Conclusions

Two conclusions may be gleaned from the results of this study. APCI penetrated the cover depth and the concentration decreased rapidly with depth. For the conditions of 50 mm of 0.45 w/c cover concrete, acid-soluble chloride contents of 0.20 to 5.5 kg/m^3 concrete, or water-soluble chloride contents of 0.19 to 5.1 kg/m^3 concrete, the APCI was not an effective posttreatment method.

Acknowledgments

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Extended Corrosion Performance of Impregnation-Treated Concrete Bridge Deck

M. C. Brown, R. E. Weyers, N. S. Berke, R. M. Weyers, and M. M. Sprinkel

A field implementation trial using the grooved deep impregnation technique with calcium nitrite as the impregnate was conducted under SHRP C-103 in July 1990. Presented are the results of the corrosion assessment surveys before treatment and at various intervals over a 9-year period. Corrosion assessment surveys included concrete cover depth, chloride content, corrosion potentials and rates, and calcium nitrite content. The results of the corrosion surveys support the conclusion that the deep impregnation with calcium nitrite has arrested active corrosion cells and has protected the bridge deck section from continued corrosion damage over the 9-year assessment period.

The extent of chloride ion–induced corrosion damage of steel-reinforced concrete bridge decks, superstructures, and substructures in the United States is well known. Present repair methods for concrete bridge elements consist of removing a limited amount of the concrete encompassing spalled and delaminated areas to a depth of 19 mm below the reinforcing steel, cleaning the exposed reinforcing steel, and backfilling the excavated areas with a concrete patch material. Sound but critically chloride contaminated concrete is left in place and subsequent spalling of the cover concrete occurs. In addition, the complete removal from exposed steel bars of chloride-bearing corrosion products is difficult, especially on the backside or underside of the reinforcing steel. Corrosion continues in these areas, but at a reduced rate, and limits the service life of the repaired areas.

An example is bridge decks in the United States. Typical repair techniques consist of scarifying the top (6 mm), patching damaged areas (spalls and delaminations), and overlaying with a low-permeable concrete. These decks have a limited service life of 22 to 26 years, regardless of the chloride exposure category—low to severe (*1*, *2*). The cause of the limited service life is the amount of critically chloride contaminated concrete left in place, which is relatively constant because repair is based on the amount of surface damage.

Background

Task 2 of the SHRP research contract C-103 (*2*) was a feasibility study of new rehabilitation techniques. The study would treat the cause of the damage rather than treat the symptoms, as typical repair techniques do. Task 5 of SHRP C-103 would field validate the construction procedures of the newly developed rehabilitation methods with the intent of monitoring the performance of the field applications for 10 years after construction.

A possible rehabilitation method is to remove all the chloride ion–induced corrosion-damaged concrete and the sound critically chloride contaminated concrete and then replace the concrete with a low-permeable con-

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crete that contains a corrosion-inhibiting admixture. The removal of the cover concrete by mechanized mechanical means is relatively inexpensive (3). However, removing the matrix concrete between the reinforcing steel and 19 mm below the reinforcing bars is relatively expensive, even when mechanized hydrodemolition is used (3).

For bridge decks, an alternative is to remove the highly chloride-contaminated cover concrete; patch the damage areas by removing the damaged concrete, cleaning the exposed bar, spraying the exposed bar with a corrosion inhibitor, and backfilling the cavity with a patch concrete containing a corrosion inhibitor; and overlay with a low-permeable concrete containing a corrosion inhibitor. The supposition is that the corrosion inhibitor will diffuse to the depth of the bar and inhibit any active corrosion before the cracking of the remaining concrete and inhibit corrosion from the chlorides diffusing through the low-permeable overlay concrete. For super- and substructure elements, the damaged and critically chloride contaminated concrete adjacent to the damage area would be removed to a depth of 19 mm below the reinforcing steel, the bar would be cleaned and sprayed with a corrosion inhibitor, and the cavity would be backfilled with a concrete containing a corrosion inhibitor.

For bridge decks with sound concrete and actively corroding reinforcing, a rehabilitation method may be deep impregnation with a corrosion inhibitor using the grooving technique. The deep grooving impregnation technique consists of cutting parallel grooves about 19 mm wide and 38 mm deep and spaced 76 mm on center. The grooves reduce the impregnation time and are used as vessels for the liquid inhibitor. The concrete is dried to a depth of 13 mm below the top reinforcing steel layer by using propane-fired infrared heaters. The concrete is considered dry when the temperature of the concrete reaches 82°C at the impregnation depth. The concrete is allowed to cool slowly to ambient temperature under an insulating mat. The grooves are filled with the liquid corrosion inhibitor and allowed to soak into the concrete. The grooves are then backfilled with a latex modified mortar containing a corrosion inhibitor.

Thirty-one inhibitors were evaluated by using a rapid screening test (4). On the basis of the results, seven inhibitors were selected for phase 2, soak impregnation through a 51-mm-wide groove over two corroding reinforcing bars in concrete laboratory specimens. If applicable, the mortar used to backfill the grooves contained a corrosion inhibitor. Of the seven inhibitor systems, the use of calcium nitrite, by ponding and addition to repair mortar, showed the greatest effectiveness. Zinc borate or sodium tetraborate ranked second (4). Two other inhibitor systems that appeared effective were amine salts in water as the ponding inhibitor and alkanolamine in the mortar, and an oxygenated hydrocarbon as a ponding inhibitor treatment only (4). Subsequent strength testing of the admixture corrosion inhibitors showed that the zinc borate severely retarded the set and strength gain of portland cement (4). Thus, the borate inhibitor concentration as an admixture had to be limited.

The following four posttreatment inhibitors were further tested on concrete specimens, which were corroding at various rates (5). Treatments consisted of removing the cover concrete to 6 mm of the top of the reinforcing bar, ponding the inhibitor for 1 or 2 days, or drying the concrete to a depth of 51 mm below the top bar and ponding the inhibitor for 1 day. The specimens were then overlaid with the appropriate admixed corrosion inhibitor concrete, where applicable (5). The four posttreatments were as follows:

- Oxygenated hydrocarbon as a ponding posttreatment corrosion inhibitor and overlaid with a low permeable concrete,
- Amine salts in water as the ponding inhibitor and an alkanolamine as the concrete admixture for patch and overlay materials,
- Calcium nitrite in water as both the ponding inhibitor and the admixture corrosion inhibitor, and
- Sodium tetraborate in water as the ponding inhibitor and admixture corrosion inhibitor.

The results showed that the oxygenated hydrocarbon is a very effective posttreatment corrosion inhibitor. The amino salts and alkanolamines and the calcium nitrite and calcium nitrite systems were effective posttreatment corrosion inhibitors (5). However, the sodium tetraborate–sodium tetraborate system was not an effective posttreatment system and thus was excluded from further test regimens. In addition, the amine salts and oxygenated hydrocarbon severely affected the bond between the overlay and substrate concretes. Further testing showed the bond could be improved by grit blasting the treated surface before placing the overlay concrete.

The ponding method for posttreatment applications of corrosion inhibitors is not very practical as a field application method. Further work concentrated on developing multiple inhibitor spray-on applications (5). The systems evaluated on slabs taken from a bridge were the oxygenated hydrocarbon, amine salts–alkanolamines, and the calcium nitrite–calcium nitrite posttreatments. The purpose of this further testing was to develop the field validation construction procedures (5).

The cover concrete of three bridge deck slabs that were removed from a Pennsylvania bridge deck was milled off with a commercial milling machine to within the depth of the top mat of reinforcing steel. Three equal spray-on applications of the posttreatment inhibitor were applied at the following rates: oxygenated hydrocarbon, 1.67 L/m^2; amine salts, 5.36 L/m^2; and calcium nitrite, 3.57 L/m^2. The slabs were then overlaid with an admixed corrosion inhibitor concrete, where applicable. On the basis of these trials, the field validation construction procedures were developed (2).

The following five posttreatment field validations were conducted (6):

- Minnesota—bridge deck posttreatment of SR-TH3 over Southview Boulevard, St. Paul;
- Washington—substructure posttreatment of Route 104 over the Hood Canal, Port Gamble;
- New York—substructure posttreatment of Elmwood Avenue over WA-198, Buffalo;
- Pennsylvania—substructure posttreatment of Route 2042 over I-81, Wilkes-Barre; and
- Virginia—deep impregnation of a bridge deck with a corrosion inhibitor (calcium nitrite), US-460 over VA-723, Christiansburg.

Because questions remained about the adequacy of the bond between the substrate and the overlay or patch concrete for the spray-on posttreatment amine salts and oxygenated hydrocarbon inhibitors, field trials of the complete posttreatment systems were not performed. The oxygenated hydrocarbon system was not field validated, and the spray-on amine salts inhibitor was not used for the amine salts–alkanolamine system. The alkanolamine admixture inhibitor was used in substructure patch concrete and in overlay concrete (6).

A previous paper presented the field validation corrosion testing results for the complete posttreatment calcium nitrite spray-on inhibitor–calcium nitrite admixture inhibitor system for the Pennsylvania substructure and the Minnesota bridge deck (7). The conclusions were based on data after 2 years for the substructure and 2.5 years for the bridge deck. The effectiveness of the calcium nitrite posttreatment system could not be determined at that time; longer assessment periods are needed to determine the effectiveness of the corrosion inhibition posttreatment system. Also, it was shown that the corrosion current density of reinforcing steel in the substrate concrete decreases under low-permeable low-slump dense concrete overlay concrete as the moisture content of the substrate concrete decreases.

This paper presents the corrosion testing of the Virginia deep impregnated bridge deck section with calcium nitrite. Details on the field validation construction process are presented elsewhere (6). Figure 1 presents a plan view of the treated area and sample locations.

RESULTS

The bridge deck section, a 2.43 × 6.1 m section of the breakdown lane, was impregnated in the summer of 1990. The bridge, built in 1967, was about 23 years old at the time of treatment. Corrosion condition surveys were conducted before treatment and 2 months and 1, 2, 4, 8, and

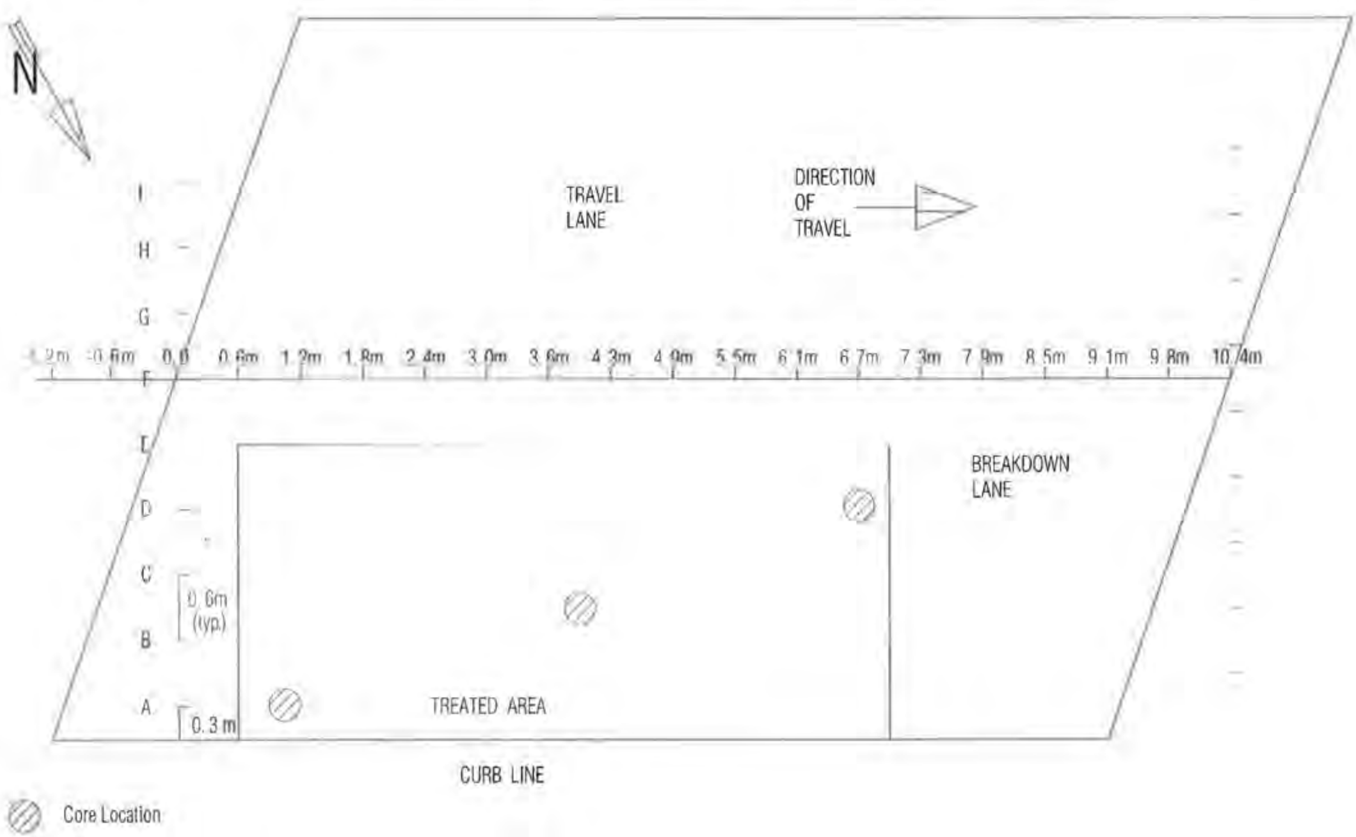

FIGURE 1 Span 1, US-460 over VA-723.

9 years after treatment. The corrosion surveys included chloride content, calcium nitrite content, corrosion potentials and rates, and delamination soundings. Presented here are the pretreatment and the 2-month and 1-, 4-, 8-, and 9-year corrosion survey results.

Delamination Survey

Table 1 presents the results of the delamination surveys. The surveys were performed by using the chain-drag method and supplemented with a 1.4-kg hammer to delineate the extent of the delaminations.

The three delaminations detected in the treated area were 0.07, 0.15, and 0.35 m^2. The number and extent of the delaminations have not increased since they were first detected 1 year after treatment. Thus, the delaminated area has remained stable over an 8-year period.

Cover Depth and Chloride and Nitrite Content

Forty cover depth readings were taken within the treated area. The readings were taken on a 0.61×0.61 m grid by using a pachometer. The average cover depth was 54 mm, the standard deviation was 6.3 mm, and the range was 31 to 62 mm. Of the 40 measurements, only 1 was less than 38 mm and only 3 were greater than 57 mm; 36 measurements were between 38 and 57 mm.

Table 2 presents the acid-soluble chloride contents for the treated area before treatment and at about 2 months and at 8 years after treatment. Two sampling techniques

TABLE 1 Delamination Survey of Calcium Nitrite–Impregnated Bridge Deck Section

Survey Date	Age of Treatment, yrs	Number Delaminations	Delaminated Area, m^2	% Area Delaminated
6/90	Pretreatment	0	0	0
7/91	1	3	0.6	4.0
9/94	4	3	0.6	4.0
6/99	9	3	0.6	4.0

TABLE 2 Chloride Content of Treated Area Before and After Treatment

Pretreatment: Sample Date 6/90, drilled powder samples

Depth, mm	Chloride Content, kg/m^3	
	A 6.7	B 3.0
13	2.6	3.1
25	2.5	2.2
38	1.6	1.7
51	1.2	1.1
64	1.2	0.94

Posttreatment:

	*Sample Date 9/90 100 mm cores			Sample Date 8/98 100 mm cores					
				A 0.9		B 3.7		D 6.7	
	A 0.9	B 3.7	D 6.7	Mortar	Conc.	Mortar	Conc.	Mortar	Conc.
6	3.6	1.3	2.1	4.9	3.1	5.5	4.6	5.9	4.1
19	2.9	2.2	0.41	5.3	2.8	7.6	4.5	5.5	3.8
32	2.1	0.9	0.23	5.0	1.9	5.6	3.4	4.4	2.5
44	2.5	1.2	0.59		1.9		2.1		1.9
59	1.8	0.88	0.53		1.6		1.5		1.7
70	2.2	0.88	0.47		1.5		0.98		1.5
82	1.5	0.65	0.47		--		1.4		1.3

	Sample Date 8/98 drilled powder samples		
	A 0.9	B 3.7	D 6.7
19	5.2	3.7	3.7
32	4.3	3.5	--
44	2.1	2.0	1.6
59	1.9	1.7	1.5
70	1.9	1.4	1.3

*9/90 chloride content is a composite value for the concrete and mortar for depths 6 to 32 mm.

were used: powder samples extracted with a 28-mm-diameter drill bit and 100-mm-diameter cores drilled with a water-cooled diamond core bit. Chloride contents presented for the 2-month, 100-mm cores are composed values for the concrete and mortar used to backfill the impregnation grooves. The 8-year values for the 100-mm cores are for the mortar and concrete portions of the cores. The drilled powder samples were taken in the concrete between the impregnation grooves. The impregnation grooves were 19 mm wide, 38 mm deep, and 76 mm on center.

As shown in Table 2, the chloride content within the reinforcing steel depth range was greater than the corrosion threshold concentration of 0.71 kg/m^3 before and at 2 months after treatment, except for sample location D6.7. Eight years after treatment, the chloride contents for both the powder and the core samples exceeded the corrosion threshold concentration for the reinforcing steel depth range of 38 to 57 mm at all locations. It is interesting to note that the chloride contents for the drilled powder and core samples are in general agreement with each other.

Table 3 presents the nitrite contents at about 2 months and at 8 years after treatment and in the same manner as the chloride contents. As shown, there has been a significant decrease in concrete nitrite content for the depth range of 44 to 82 mm. Other depths cannot be compared because the 2-month measurements at depths less than 38 mm are composite mortar-concrete concentrations.

The nitrite-to-chloride ratios for the reinforcing steel depth range 38 to 57 mm ranged from 20 to 1.3 at 2 months after treatment and 3.8 to 0.95 at 8 years after treatment. Thus the nitrite-to-chloride ratios were near or greater than the generally accepted inhibition ratio of 1.0 at 8 years after treatment.

Corrosion Potential and Rates

Table 4 presents the average corrosion potentials, standard deviation, and coefficient of variation for the four grid lines, A through D, within the treated area. Eleven potential measures, 0.6 m apart, were taken along each grid line. Grid line A is 0.3 m from the curb line and grid lines A, B, C, and D are 0.6 m apart. See Figure 1. Measurements were taken before treatment and about 1, 4, 8, and 9 years after treatment.

Before treatment, grid A potentials, adjacent to the curb line, had a high potential for active corrosion. The probability of active corrosion was very low along grid lines B, C, and D, with the lowest probability of active corrosion along grid line D, the farthest from the curb line. Over the 9-year measurement period, grid line A corrosion potentials became more positive and thus have a lower probability of active corrosion. Grid lines B, C, and D became more negative. Of interest is the observation that the corrosion potentials throughout the treated area became more uniform, as illustrated by the decreasing coefficients of variation.

TABLE 3 Nitrite Contents and Nitrite-Chloride Ratios

Posttreatment: Nitrite contents, ℓ/m^3 (30% solution of calcium nitrite)

Depth mm	*Sample Date: 9/90, 100 mm cores			Sample Date: 8/98, 100 mm cores					
				A 0.9		B 3.7		D 6.7	
	A 0.9	B 3.7	D 6.7	Mortar	Conc.	Mortar	Conc.	Mortar	Conc.
6	30	47	36	32	14	57	26	48	16
19	27	44	52	22	10	68	31	51	34
32	31	52	63	17	6.5	57	27	48	23
44	12	26	40		6.5		18		17
59	10	33	40		6.0		22		17
70	9.5	34	46		6.0		17		17
82	4.5	19	48				23		13

*9/90 nitrite content is a composite value for the concrete and mortar for depths 6 to 32 mm.

Posttreatment Concrete Nitrite-Chloride Mass Ratio

Depth mm	Sample Date 9/90, 100 mm cores			Sample Date 8/98, 100 mm cores		
	A 0.9	B 3.7	D 6.7	A 0.9	B 3.7	D 6.7
32	–	–	–	0.88	2.10	2.4
44	1.3	6.0	18	0.95	2.3	2.4
59	1.6	9.9	20	0.99	3.8	2.6
70	1.6	1.0	26	1.1	4.6	3.0
80	0.78	8.0	27	–	4.1	2.6

TABLE 4 Corrosion Potential Surveys of Calcium Nitrite–Impregnated Area, Average, Standard Deviation, and Coefficient of Variation (CSE, mV)

Statistical Parameter	Date									
	*6/90	7/91	9/94	8/98	6/99	*6/90	7/91	9/94	8/98	6/99
	Grid Line A					Grid Line B				
$\overline{X}$	412	323	312	314	284	184	287	273	288	293
σ_{n-1}	119	45	35	24	28	50	21	46	33	49
CV, %	29	14	11	8	10	27	7	17	11	17
	Grid Line C					Grid Line D				
$\overline{X}$	142	244	246	262	311	91	284	248	246	283
σ_{n-1}	33	23	26	24	22	32	48	46	29	23
CV, %	23	9	11	9	7	35	17	19	12	8

*Pretreatment measurements

Table 5 presents the linear polarization (3LP) corrosion rates at 10 locations within the treated area. As shown, grid line A corrosion rates are considerably higher than those for grid lines B and D before treatment. Over the 9-year measurement period, the corrosion rates along grid lines A and B have decreased considerably, and grid line D has remained at a relatively low rate of corrosion. At 8 and 9 years after treatment, all corrosion rates are relatively low, although the chloride content at the reinforcing steel depth is considerably above the corrosion threshold concentration at the same measurement locations. See Table 2.

Discussion of Results

Over the 9-year corrosion assessment period, the chloride contents have increased to above the corrosion threshold concentration within the treated area, the calcium nitrite concentrations have decreased at the measurement depths, the corrosion potentials have become almost uniform, and the nitrite-to-chloride ratio has remained near or above 1.0. During this period, the corrosion rates have decreased to a near uniform low rate. Although delaminations were detected within the treated area 1 year after treatment, it may be that the delaminated areas were small at the time of treatment and thus were not detected until the 1-year posttreatment condition assessment, or the chloride content and corrosion rate may have been too high for the treatment to be effective in these areas. However, of interest is the observation that the delaminated areas have not increased in the 8-year period since they were detected.

Conclusions

The following were found for deep impregnation of the treated area with calcium nitrite, over the 9-year assessment period:

- Growth of delaminations beyond 1 year after treatment was stopped.
- Corrosion potentials have become more uniform, with a lower probability of active corrosion.
- Corrosion rates have decreased.
- Chloride contents have increased to above the corrosion threshold concentration of 0.71 kg/m^3 at the reinforcing steel depth.

TABLE 5 3LP Corrosion Rate Measurements of Calcium Nitrite–Impregnated Area ($\mu A/cm^2$)

Grid Location	Measurement Date				
	*6/90	7/92	9/94	8/98	6/99
A 1.8	6.4	1.3	4.6	1.0	0.9
A 4.2	7.3	2.8	2.3	—	—
A 6.7	1.5	1.5	1.0	—	—
B 0.6	1.1	2.5	0.5	—	—
B 3.0	1.2	1.7	0.5	—	—
B 4.2	0.8	2.6	1.5	0.8	0.6
D 0.6	0.8	1.6	0.4	—	—
D 1.2	0.7	2.0	0.6	0.9	0.8
D 3.7	—	—	0.5	—	—
D 6.7	—	—	—	0.6	0.7

*Pretreatment measurements

- Calcium nitrite concentrations have decreased at the measurement depths.
- Calcium nitrite–chloride ratio has decreased from a range of 20 to 1.3 down to a range of 3.8 to 0.95 at the measured reinforcing steel depths.
- For the reported assessment period of 9 years, depth impregnation with calcium nitrite has been an effective corrosion posttreatment technique.

ACKNOWLEDGMENTS

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Rapid Rehabilitation or Replacement of Bridge Decks Under Concurrent Traffic Conditions

George E. Ramey

The Alabama Department of Transportation (ALDOT) has more than 4.8 km (3 mi) of major Interstate bridges near downtown Birmingham with significant levels of deck cracking and deterioration. The bridges are part of the I-65 and I-59/20 Interstate highway system through the city and are approximately 30 years old. About 5 to 7 years ago, ALDOT bridge inspectors began to see longitudinal cracks in the top of the deck above the edges of the support girders. These cracks are continuing to grow in length and width and are beginning to combine with older transverse cracks to form surface spalls. ALDOT must make decisions on rehabilitation actions for the Birmingham decks in the near future. Toward this end, ALDOT is looking closely into what other states and highway agencies are doing, traffic demands and the need for additional lanes, the remaining fatigue and service life of the steel girder superstructures, punching shear load testing, delamination and deterioration of the existing decks, and placement of deck test sections using different rehabilitation strategies.

More than 4.8 km (3 mi) of major Interstate bridges [three to five lanes wide, with approximately 55 742 m^2 (600,000 ft^2) of deck] near downtown Birmingham, Alabama, have significant levels of deck cracking and deterioration. The bridges are part of the I-65 and I-59/20 Interstate highway system through the city and are approximately 30 years old. Typical photographs showing the state of cracking and deterioration of the I-65 and I-59/20 bridges are presented in Figures 1 through 4. Obviously, the decks are showing significant cracking. Alabama Department of Transportation (ALDOT) bridge inspectors indicate that about 5 to 7 years ago they began to see longitudinal cracks in the top of the deck above the edges of the support girders. These cracks are continuing to grow in length and width and are beginning to combine with older transverse cracks (which are almost everywhere) to form surface spalls, as shown in Figure 4.

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ALDOT's primary concerns about the Birmingham I-65 and I-59/20 decks are as follows:

- Inadequate traffic lanes and traffic capacity, on I-65 and on I-59/20 from the I-59/20 juncture to the I-65 interchange in particular;
- Significant levels of live load deflections and out-of-plane movement of the deck superstructure system; in turn, these are probably the major contributors to the distresses indicated below;
- Significant level and rate of increase of deck cracking and deterioration, requiring ever-increasing maintenance attendance in the form of surface spall and pothole repairs (which generally require full-depth patches); these probably are reducing the bending stiffness in both the longitudinal and the transverse directions, are leading to greater deflections and cracking, and will eventually lead to deck-punching shear failures;
- Extensive fine cracking on the deck undersides, with a concern for future underside spalling problems, which would create a safety hazard and additional maintenance requirements; and

FIGURE 1 Close-up of transverse cracking on I-65 bridge.

- Past history of fatigue problems with diaphragms, diaphragm-to-girder connections, and support girders (at locations of transverse diaphragms) and a concern that the girders may be approaching their fatigue limit and will need to be replaced.

ALDOT must make decisions on rehabilitation actions for the Birmingham decks in the near future. Toward this end, ALDOT is looking closely into the following:

- What other states and highway agencies do in similar cases;
- Traffic demands and planning to identify the need for additional lanes on these bridges in the near future (if additional lanes are justified, they will be added first to ease the traffic congestion during later staged-construction deck rehabilitation);
- An assessment of remaining fatigue and service life of the steel girder superstructures through field strain gage measurements and analytical analysis;
- Developing the capabilities to perform punching shear load testing within ALDOT's bridge load testing section to allow the assessment of punching shear capacity and the imminence of deck structural failure via punching shear;

FIGURE 2 Underside of I-65 bridge.

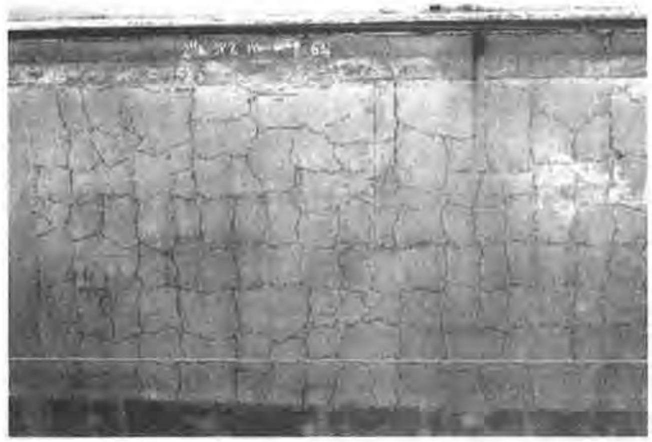

FIGURE 3 Close-up of underside of I-65 bridge at midspan with hairline cracks highlighted.

- Assessing the state of delaminations and deterioration of the existing decks to determine the viability of employing deck overlays as an effective rehabilitation strategy; and
- Placement of deck test sections employing different rehabilitation strategies (deck replacements and deck overlays) to evaluate their construction friendliness, requirements for traffic constraints, costs, and performance and estimated longevity when placed in a staged and rapid construction manner.

The research described below is part of ALDOT's investigative work on the Birmingham bridge deck problem.

Phase 1 Research Work

Before ALDOT could decide on the appropriate rehabilitation actions for the Birmingham bridge deck, several questions had to be answered:

FIGURE 4 I-65 deck surface spall.

• What are the causes of the deck cracking and deterioration?
• What is the present state of structural adequacy of the bridge decks?
• What is the remaining service life of the bridge superstructure girder?
• What are the most viable deck rehabilitation and deck replacement options?
• What are the construction friendliness, required traffic disruption, and costs of the most viable deck rehabilitation and deck replacement options?

The objectives of the Phase 1 research were to answer some of these questions, namely, to

• Identify the causes and failure chronology for the Birmingham bridge decks,
• Survey other state DOTs to determine how they are addressing this problem, and
• Identify effective and efficient deck rehabilitation and replacement procedures that are workable for Alabama operating conditions and under staged construction and concurrent traffic conditions.

From the Phase 1 work, it appears that the deck cracking is primarily the result of early drying and thermal shrinkage, early concrete obstructed settlement, thin and flexible deck [approximately 16.5 cm (6.5 in.) thickness], light and flexible superstructure, and heavy traffic volume and truck loading (80,000 one-way average daily traffic in 1998).

The typical failure chronology for bridge decks in Alabama appears to be as follows:

• A significant level of early transverse shrinkage cracking;
• Growth in width of transverse cracks due to crack movement and abrasion from traffic and environment loadings;
• Development of longitudinal cracks at girder edges due to poor longitudinal distribution of truck tire loadings (in part because of extensive transverse cracking);
• Reduced bending stiffness in both the transverse and the longitudinal direction due to crack growth, which in turn leads to increased deck cracking;
• Local surface spalling requiring ever-increasing maintenance attendance; and
• Eventual deck punching shear failures.

The most viable rehabilitation options for the Birmingham Interstate bridge decks identified in the Phase 1 work were to rehabilitate the bridge decks by using overlays (for 10- to 20-year life extension), replace the decks, add longitudinal girders to strengthen and stiffen the existing deck and superstructure, and replace the bridge superstructures.

Which rehabilitation strategy would be the most cost-effective depends on the structural adequacy of the existing concrete decks and their estimated remaining service life, along with the remaining service life of the bridge girders. Table 1 shows a matrix of rehabilitation strategies for various estimates of remaining life for the deck and support girders. Work is under way to make best estimates of these remaining lives.

To determine how other states address their deck deterioration problems, a short survey questionnaire was mailed out. Forty-one state DOTs responded. Some results of the survey are shown in Figures 5 and 6. The principal investigator (PI) also visited several states that were performing deck rehabilitation at the time. Georgia was using rapid setting Type III cement concrete structural overlay. Kentucky was using 3.17-cm (1.25-in.) rapid setting latex modified concrete overlay. California was using 19-mm (0.75-in.) polyester polymer concrete overlay. And New York was using exodermic precast deck panel deck replacement.

Select photographs of these rehabilitations in progress are shown in Figures 7 through 14.

TABLE 1 Rehabilitation Strategies for Various Combinations of Estimated Remaining Life for Support Girders and Deck

Deck Estimated Remaining Life	Support Girders Estimated Remaining Life		
	15 Years	30 Years	50^{+} Years
8 years	Overlay in 7 years	Replace deck in 7 years	Replace deck in 7 years
16 years	Replace superstructure in 14 years	Overlay in 15 years	Replace deck in 15 years
24 years	Replace superstructure in 14 years	Replace superstructure in 23 years	Replace deck in 23 years

NOTE: An alternate strategy to those indicated is to add a support girder between each existing girder. This is felt to be a viable option for situations where the estimated remaining life of the girders and the deck is 15 years or greater.

Phase 2 Research Work

On the basis of the Phase 1 work, four bridge deck replacement test sections will be placed in Birmingham in Phase 2. The replacement systems will be as follows:

- A continuous precast prestressed stay-in-place (SIP) form system with a cast-in-place (CIP) concrete topping (Nebraska University deck design);
- An exodermic steel panel system with a CIP concrete topping;

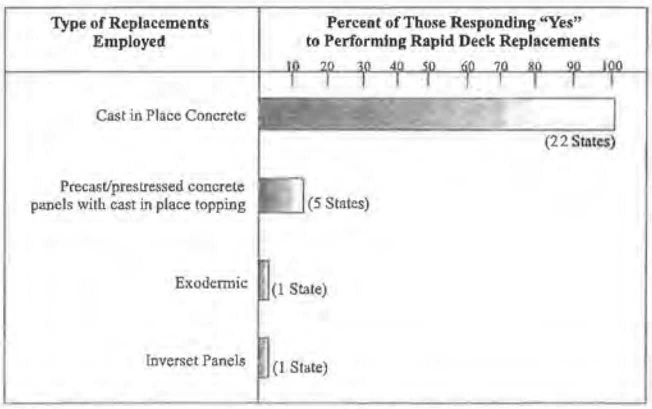

FIGURE 5 Summary of type of deck replacements employed by other states in urban setting with staged construction and concurrent traffic (22 states).

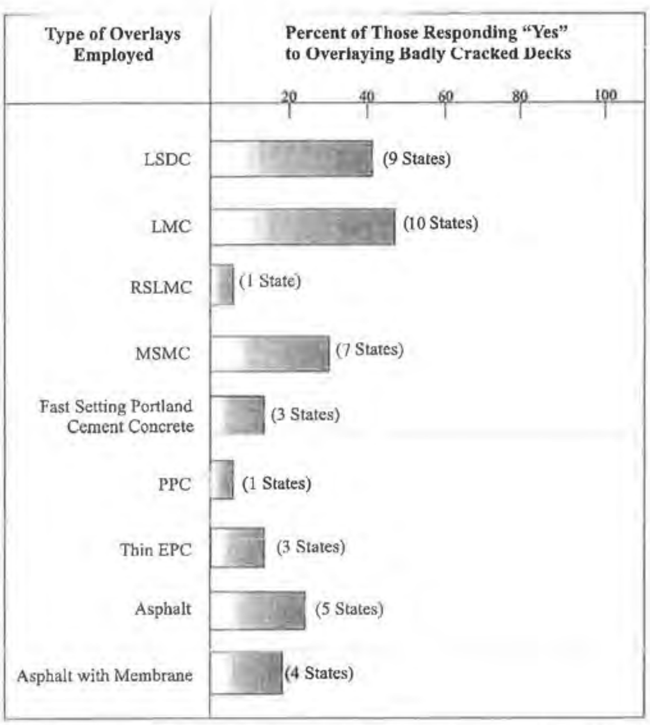

FIGURE 6 Summary of type of deck overlays employed by other states on badly cracked decks (23 states).

FIGURE 7 Hydrodemolition portion of deck near an expansion joint with two sizable blow-outs—I-285 bridge, Georgia.

FIGURE 8 Strip to be overlaid just after completion of hydrodemolition looking south on I-285 bridge, Georgia.

FIGURE 9 Typical deck damage at joints, Kentucky bridge.

FIGURE 10 Typical deck damage away from joints, Kentucky bridge.

FIGURE 11 Applying deck primer—Caltrans's PPC overlay.

FIGURE 12 Screeding Caltrans's PPC overlay.

FIGURE 13 Exodermic panels in off-bridge staging area, Tappan Zee Bridge.

FIGURE 14 Setting of first exodermic panel, Tappan Zee Bridge.

- A conventional steel grid panel system with a CIP concrete topping; and
- A SIP metal form system with a CIP concrete topping.

Additionally, a superstructure stiffening and strengthening system, consisting of adding a girder line (from the underside) between the existing girders, will be placed for one bridge span. A major advantage of this rehabilitation strategy is that most of the work can be performed from the underside of the bridges with little disruption in traffic. Two other significant attractions of this strategy are that it will significantly stiffen and strengthen the deck-superstructure system, and it will reduce fatigue-inducing live-load stresses in the existing girders and deck. Sketches of these replacement and stiffening systems are shown in Figures 15 through 18.

Each of the five systems will be placed for one span of the bridge in a staged construction manner so that traffic, although restricted, will be able to continue. Each system will be monitored to document its construction "friendliness," required lane closure time, costs, and first-year performance.

In addition, four bridge deck overlay test sections will be placed and monitored in Birmingham in Phase 2 in the same manner. The overlay systems will be a 12.7-mm to 19-mm (0.75-in.) asphaltic based with polymer-modified asphalt emulsion binder NOVACHIP overlay; a 9.5-mm (3/8-in.) Polycarb-Flexogrid epoxy polymer concrete overlay; a 12.7-mm Thermo-Chem epoxy polymer concrete with glass fiber grid reinforcement overlay; and a 19-mm polyester polymer concrete overlay [California Department of Transportation (Caltrans) overlay].

In the Phase 2 work, the project PI will work with ALDOT's bridge load testing section to add bridge deck punching shear load testing to its abilities. In turn, the PI and the testing section will perform punching shear field tests on an AL-79 bridge north of Birmingham (after it is taken out of service in 2000) to assess punching shear capacity at cracked and uncracked deck locations. In addition to measuring the punching shear failure loads, the tests will measure vertical deflections at the load point to assess the deck P-Δ behavior and signature.

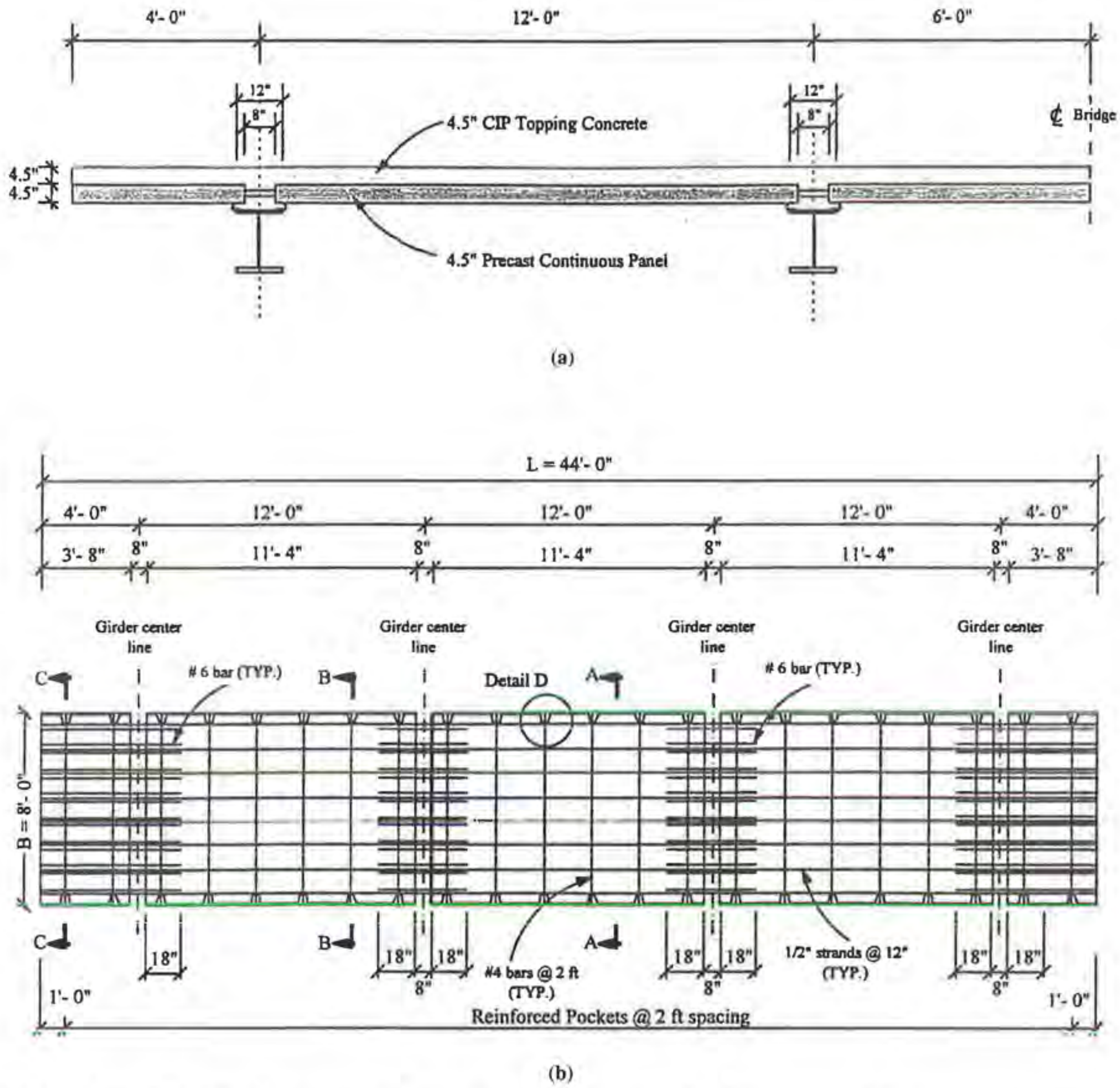

FIGURE 15 Nebraska University continuous prestressed concrete SIP form system: (*a*) cross section and (*b*) plan view. (From report on NCHRP Project 12-41 by M. K. Tadros.)

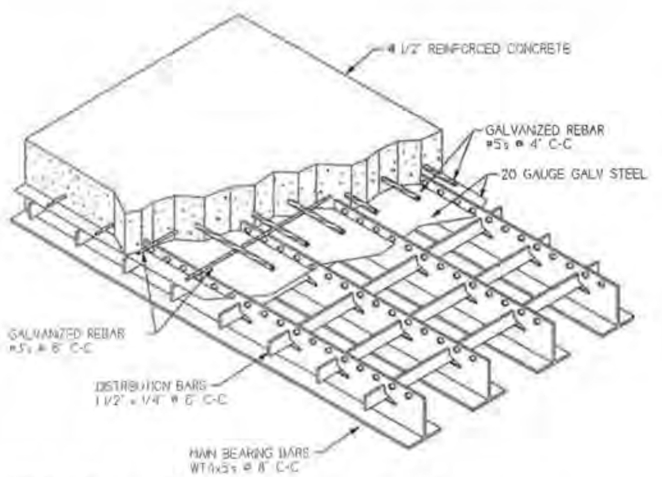

FIGURE 16 **New (1998) exodermic deck panel.**

Observing the punching shear P-Δ curves for the AL-79 bridge will provide insight on the expected service load, first slip load, and failure load versus deflection behavior, which in turn will be helpful when the results of punching shear proof load testing are analyzed. Additionally, punching shear load testing of some longitudinal deck crack repair and deck patching schemes will be performed to assess their performances. It should be noted that the current punching shear deck repair procedure usually results in fairly early new cracking at each longitudinal end of the repair, and later spalling or punching shear failures at these locations. Lastly, punching shear proof load tests on I-65 and I-59/20 bridges will be conducted at select locations to assess adequacy of the deck capacity via proof loading to three to four times the anticipated maximum truck wheel load.

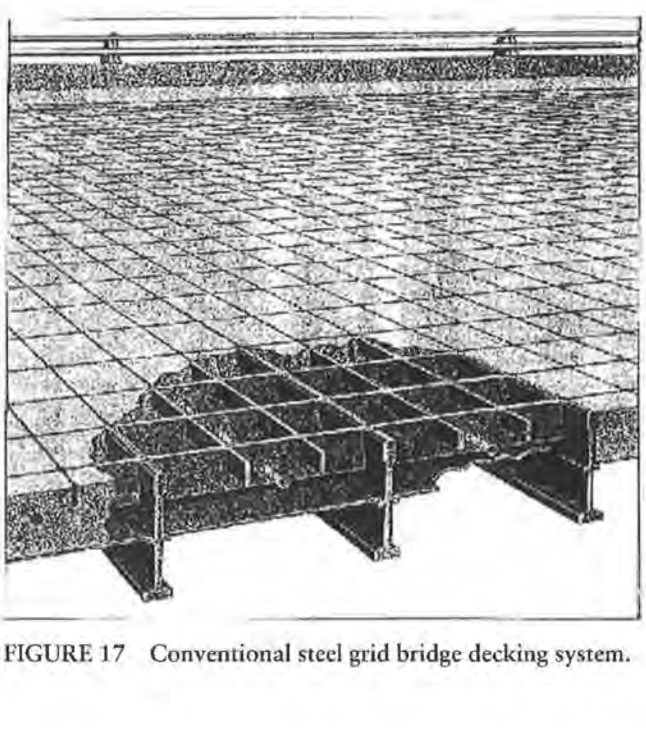

FIGURE 17 **Conventional steel grid bridge decking system.**

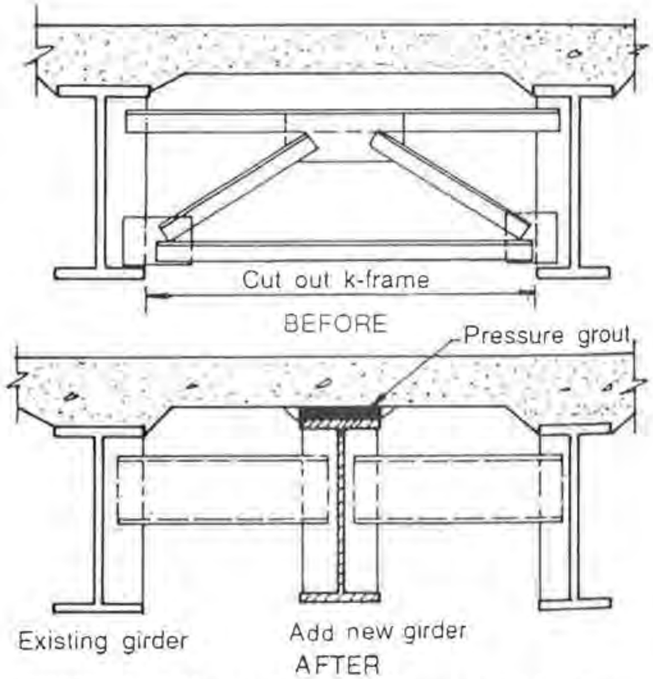

FIGURE 18 **Adding girders. (From *Concrete Bridges*, by V.K. Raina.)**

In addition to the I-20/59 and I-65 bridges through Birmingham showing considerable deck cracking and deterioration, these same steel girder bridges have experienced significant fatigue cracking, especially at cross-framing and diaphragms. Thus, an evaluation of the remaining life of the steel girders on the Birmingham Interstate highway bridges is needed before a good decision about how to handle the bridge decks can be made.

Mike Stallings of Auburn University is working with ALDOT to evaluate the remaining life of the steel girders of the Birmingham Interstate bridges. A brief outline summary of Stallings' work is as follows:

1. Determine the common bridge types, span lengths, and types and locations of fatigue-prone details such as coverplate ends, transverse stiffener welds, and diaphragms. This information will be determined from the structural drawings and field inspections, and it will be used to identify locations where strain measurements are needed and to provide information for fatigue life calculations.
2. Determine past traffic histories for the roadway and bridges from ALDOT records to estimate how much of the total fatigue life has already been used.
3. Estimate traffic-induced stress ranges at the fatigue-prone locations for calculating remaining fatigue life. These will be estimated first by analytical analysis and later by field measurement, because accurate estimates of

the stress ranges are critical to successfully predicting remaining fatigue life.

4. Field strain gauging and strain measurements will be made at all fatigue-prone locations in four to six typical bridge spans. These data will be reduced and analyzed.

5. Results from the current literature will be used to determine best estimates of the fatigue resistance of the various types of fatigue-prone details found on the Birmingham bridges. Fatigue-resistance relationships given in *NCHRP Report 299* (*1*) appear to be the best currently available.

6. Project future traffic volumes for the Birmingham roadways and bridges. Remaining fatigue-life calculations provide a number of fatigue cycles or truck crossings until failure. Thus, projected future traffic volumes are needed to convert the remaining fatigue cycles into numbers of remaining years of service life.

7. Calculate the remaining fatigue life for each of the fatigue-prone locations for which field strain measurements were made. The number of years until failure predicted at a significant fraction of these locations will be considered the best estimate of remaining fatigue life.

CLOSURE

The Phase 1 and Phase 2 work described, in conjunction with the work on support-girder remaining fatigue and service life, will provide ALDOT with the information needed to make informed and good decisions on the best ways to rehabilitate the Birmingham Interstate bridge decks. That is, Should ALDOT overlay the decks? with what type of overlay? Should ALDOT replace the decks? in what manner? Or should ALDOT replace the whole bridge superstructure?

ACKNOWLEDGMENTS

This ongoing research is sponsored by ALDOT and the Auburn University Highway Research Center.

REFERENCE

1. Moses, F., C. G. Schilling, and K. S. Raju. *NCHRP Report 299: Fatigue Evaluation Procedures for Steel Bridges*. TRB, National Research Council, Washington, D.C., 1987.

Part 5

MAINTENANCE RESEARCH

Customer Perceptions and Expectations of Minnesota's Bare Pavement Product

Gary Niemi

In recent years the road maintenance division of the Minnesota Department of Transportation (MnDOT) has redefined its role, moving from a traditional focus on internal activities to an external-looking vision of customer-based products and services. Toward this end MnDOT conducted research to understand the attributes of its bare pavement product (the result of MnDOT's snow removal operations) that are important to the customer as well as to determine customer expectations for levels of service in different highway environments. The research was designed to measure the effects on highway consumers of six levels of snow removal on three different classes of roads throughout the state—two-lane roads, four-lane divided highways, and Interstate highways—as well as to determine whether driving habits or opinions vary by demographic group. Study participants viewed winter driving road conditions on videotape, then documented their opinions and reactions on a self-administered questionnaire. In partnership with local community groups and organizations, a market research firm was commissioned to assist with the study, including identifying and recruiting study participants. Results of this research will be used to improve delivery of MnDOT's snow removal operations in order to better meet the needs and desires of its customers.

The research was designed to meet the following objectives:

1. To measure the impact of six levels of snow removal service on the willingness of drivers to use the roads;

2. To identify driving comfort levels for the six levels of snow removal service;

3. To identify acceptability levels for the six levels of snow removal service;

4. To determine how the above opinions and perceptions (willingness to drive, comfort level, and acceptability) change, if at all, as time passes after the end of a snowfall;

5. To assess the above opinions and perceptions for three different classes of roads: two-lane roads, four-lane divided highways, and Interstate highways;

6. To gather customer input from all areas of the state, specifically the Greater Minnesota and Metro regions, the North/North-Central region, the West-Central/Northwest regions, and the southern part of the state; and

7. To determine whether driving habits or opinions vary for specific demographic groups.

Methodology

The study's methodology was designed to assess customer opinions and perceptions concerning three classes of roads: two-lane roads, four-lane divided highways, and Interstate highways. Study participants were invited to a central location where they viewed winter driving road conditions on videotapes and recorded their reactions on a self-administered questionnaire. To eliminate respondent fatigue, only four of the six winter road conditions (reflecting four of the six levels of MnDOT snow removal service) were shown to a participant for a single class of road. Selection of service level was accomplished by having each individual view the worst level (snow-covered, compacted), the best level (fully bare), and two of the four in-between winter driving road conditions (Figures 1 to 6). Care was taken to assure that each of the

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FIGURE 1 Snow-covered, compacted (worst).

FIGURE 2 One intermittent wheelpath.

FIGURE 3 Two intermittent wheelpaths.

FIGURE 4 Two lanes plowed with centerline covered and no edge lines showing.

FIGURE 5 Two lanes plowed with centerline covered but edge lines showing.

FIGURE 6 Fully bare (best).

four in-between winter road conditions received an equal number of evaluations.

For Greater Minnesota, two-lane and four-lane highways were evaluated, therefore each participant evaluated eight different videos. In Metro Minnesota, two-lane roads, four-lane divided highways, and Interstate highways were evaluated, and each participant evaluated 12 different videos.

Participants in each city were invited, in groups, to a central location. Each group viewed a set of four winter driving road condition videos for a specific road class. After each video ended, a still photograph from the video was placed before the participant as a reminder of the winter driving road condition being evaluated. Participants were then instructed to consider the following information while rating the road conditions:

- Roads in the videotapes showed various levels of snow removal after a 3-in. to 4-in. snowfall.
- The snowfall had ended at 3 a.m. (in the Metro area some questions concerned snowfalls that ended at 3 p.m. or 6 p.m.).
- The driver need not be concerned with ice on the roads.
- The wind had diminished when the snowfall ended and remained calm.
- The temperature had remained constant throughout the day.

Representatives of the market research firm then administered a group interview, and participants registered their opinions on a self-administered questionnaire. Upon completion of the questionnaire, market research firm representatives ensured they had been filled out correctly and that instructions had been followed accurately.

In the interest of using its research funds judiciously, MnDOT and the market research firm it commissioned used the proven technique of partnering with local community groups and organizations to identify and recruit study participants. Groups and organizations who committed to the study followed guidelines provided by the market research firm in qualifying and recruiting study participants from their membership lists or rosters. For each recruited participant who completed the study, the recruiting group or organization received a $15 donation. This method provided a high level of respondent participation at a low per-interview cost. Building in variation across organizational type and consumer market also aided in securing a demographically representative sample.

Study Limitations and Assumptions

Because of the nature of the research design that was necessary to address study objectives within a reasonable budget, the following study limitations should be considered when interpreting the results:

1. First, the sample is a strict random probability sample. Because it was believed that study participants could give a more accurate expression of their opinions by viewing a moving videotape of road conditions, it was necessary to invite participants to a specific location. As a result, participants from only 12 general areas of Minnesota are included in the study. To mitigate potential bias, test locations were carefully chosen to reflect populations similar to those of other cities across Minnesota while also providing geographical dispersion. Further, in each market recruiting was conducted through the rosters and membership lists of local organizations. While this recruiting method has the potential to over- or underrepresent certain demographic groups, experience has shown that it also has the advantage of gaining cooperation from individuals who might not otherwise give their time to research. This is especially significant in light of the lower levels of cooperation being experienced more often in research among these groups due to answering machines or caller ID telephone services.
2. Second, the videotape illustrating the second-best road condition ("the center of the lane plowed with centerline covered but edge lines showing") appears to have included sections of road that were more difficult to drive on than those shown in the third-best level of road maintenance service ("the center of the lane plowed with centerline covered and no edge lines showing"). It is believed that the video of the second-best winter driving road conditions (edge lines showing) included curved roads and may also have given the impression of icy roads. While participants were told that the roads did not have icy patches, it is possible that the video impressions did not permit research participants to fully comprehend this road condition.

Summary of Findings

The survey was structured to learn the conditions under which MnDOT's customers are willing to drive, how acceptable MnDOT's level of service is to highway consumers, and how comfortable consumers are while driving on roads that reflect varying levels of MnDOT service. MnDOT was also interested in learning how tolerant drivers are as time passes after the end of a snow event and if the willingness to drive differs depending on the purpose of a trip.

Following are the results of the survey:

1. Minnesotans said they would drive to work under any road condition after a 3-in. to 4-in. snowfall, even though few road conditions are rated as acceptable or comfortable for driving.

• Most Minnesota drivers (80 percent or more depending on test area) said they would drive to work at their usual time on any of the six presented road conditions. This was true for the three road types [two-lane roads, four-lane divided highways, and Interstate highways (Interstate highways were rated only in the Metro area)] in both Greater Minnesota and in the Metro area at 6 a.m. 3 h after a snowfall had ended, and between 7 a.m. and 9 a.m. 4 to 6 h after a snowfall had ended. Most Metro drivers said they would also drive home from work between 4 p.m. and 6 p.m. on any road type or in any condition if the snowfall ended at 3 p.m. (1 to 3 h before leaving for home).

• Most Minnesota drivers (80 percent or more) indicated they are comfortable driving to work only under the following road conditions, which they also rate as acceptable at 6 a.m. and 7 a.m. to 9 a.m. [and also 4 p.m. to 6 p.m. (asked in the Metro area only)]:

– Fully bare conditions for all three road types in all areas,

– Centerline covered with edge lines showing (four-lane divided highways in Greater Minnesota only), and

– Centerline covered and edge lines not showing (two-lane roads and four-lane divided highways in Metro area only and Interstate highways).

• In general, Minnesota drivers indicated they are not comfortable driving to or from work under the following road conditions, which are also not rated as acceptable at any time of the day and on any of the three categories of roads:

– Two intermittent wheelpaths,

– One intermittent wheelpath, or

– Snow-covered, compacted roads.

2. Most Minnesotans said they would drive to an appointment after a 3-in. to 4-in. snowfall under any four-lane divided highway or Interstate highway condition. Some two-lane road conditions limited respondents' expressed willingness to drive to appointments earlier in the day. Again, few road conditions were rated as acceptable or comfortable for driving to an appointment, and Minnesota drivers were especially critical of four-lane divided highway conditions.

• Most Minnesota drivers (80 percent or more) in both Greater Minnesota and the Metro area indicated they would be willing to drive an appointment between 7 and 9 a.m., 4 to 6 h after a snowfall has ended, under the following winter driving conditions:

– Fully bare conditions (all road types),

– Centerline covered with edge lines showing (all road types),

– Centerline covered and edge lines not showing (all road types),

– Two intermittent wheelpaths (four-lane divided highways and Interstate highways only), or

– One intermittent wheelpath (four-lane divided highways and Interstate highways only).

• For the time of noon, most respondents said they would drive to an appointment under any winter driving condition and on any road type except for snow-covered, compacted two-lane roads. This was true for both Greater Minnesota and the Metro area.

• Most Minnesota drivers (80 percent or more) indicated they would be comfortable driving to an appointment in either Greater Minnesota or the Metro area only under the following road conditions, which they also rate as acceptable at either 7 a.m. to 9 a.m. or noon:

– Fully bare conditions (two-lane roads and Interstate highways only) and

– Centerline covered and no edge lines showing (two-lane roads and Interstate highways only).

• In general, few Minnesota drivers said they would be comfortable driving to an appointment under the following road conditions, which few rated as acceptable:

– Four-lane divided highways with two intermittent wheelpaths,

– Four-lane divided highways with one intermittent wheelpath, or

– Snow-covered and compacted roads.

3. The willingness to drive to school on two-lane roads was limited to at least two intermittent wheelpaths or better conditions such as cleared roads. Minnesotans said they would drive to school under any four-lane divided highway or Interstate highway road conditions between 7 and 9 a.m. after a 3-in. to 4-in. snowfall.

• Most Minnesota drivers (80 percent or more) in both Greater Minnesota and the Metro area said they would be willing to drive to school between 7 a.m. and 9 a.m. 4 to 6 h after a snowfall has ended under the following winter driving conditions:

– Fully bare conditions (all road types),

– Centerline covered with edge lines showing (all road types),

– Centerline covered and no edge lines showing (all road types),

– Two intermittent wheelpaths (all road types),

– One intermittent wheelpath (four-lane divided highways and Interstate highways only),

– Snow-covered, compacted conditions (four-lane divided highways in Greater Minnesota and only Interstate highways in the Metro area).

• Most respondents (80 percent or more) driving to school in either Greater Minnesota or the Metro area indicated they would be comfortable driving on very few road conditions and would also find few road conditions acceptable. Only the following road conditions were rated as comfortable to drive under or acceptable at 7 a.m. to 9 a.m.:

– Fully bare conditions (all road types) and

– Centerline covered and no edge lines showing (two-lane roads or four-lane divided highways in Greater Minnesota and only Interstate highways in the Metro area).

4. After-school activities (between 4 p.m. and 6 p.m.), such as extracurricular practice, would be severely limited according to respondents if the roads had not been cleared.

- In Greater Minnesota, if a snowfall has ended at 3 a.m. (13 to 15 h prior to 4 p.m. to 6 p.m.), most respondents (80 percent or more) said they would be willing to drive to such activities as practice and workouts under the following winter driving conditions:

  – Fully bare conditions (two-lane roads only),

  – Centerline covered with edge lines showing (two-lane roads only), and

  – Centerline covered and no edge lines showing (two-lane roads only).

- In the Metro area, if a snowfall has ended at 3 p.m. (1 to 3 h prior to 4 p.m. to 6 p.m.), most respondents (80 percent or more) said they would not be willing to drive to such activities as practice and workouts under any winter driving conditions.

- No winter driving conditions in the Metro area were considered as acceptable or rated as making respondents feel comfortable while driving to such activities as practice and workouts between 4 p.m. and 6 p.m. 1 to 3 h after a snowfall has ended. Only the following road conditions were rated as comfortable to drive under or as acceptable at 4 p.m. to 6 p.m. in Greater Minnesota, 13 to 15 h after the snowfall has ended:

  – Fully bare conditions (two-lane roads or four-lane divided highways in Greater Minnesota only) and

  – Centerline covered and no edge lines showing (two-lane roads in Greater Minnesota only).

5. Shopping was the most seriously curtailed activity after a snowfall. This was in part a result of a percentage of respondents who indicated they did not shop at certain times of the day and also a result of the discretionary nature of shopping, a task that can easily be rescheduled to a nonsnow day.

- Only a portion of Minnesota drivers (60 to 79 percent) said they would be willing to drive for the purpose of shopping under the following winter driving conditions:

  – Fully bare conditions [Greater Minnesota two-lane roads in the morning or noon only (not in the late afternoon), Greater Minnesota four-lane divided highways at any time of the day, Metro two-lane roads at any time of the day, Metro four-lane divided highways at noon or in the afternoon, and Metro area Interstate highways at any time of the day], and

  – Centerline covered and no edge lines showing (all road types).

- Most drivers (80 percent or more) in either Greater Minnesota or the Metro area say they would be comfortable driving for shopping purposes under the following two winter driving road conditions, which they would also find acceptable:

  – Fully bare conditions (all road types in Greater Minnesota and two-lane roads and Interstate highways in the Metro area) and

  – Centerline covered and no edge lines showing (two-lane roads in Greater Minnesota and two-lane or Interstate highways in the Metro area).

Conclusions and Recommendations

Conclusions

Acceptability levels for all road conditions closely match comfort levels. This is true throughout the study for all road conditions on all classes of roads. As comfort levels increase, so do levels of acceptability.

Levels of acceptability and driving comfort, however, do not affect willingness to drive as might initially be expected. In numerous situations throughout the study, drivers' measured comfort levels and acceptability of road conditions were under 30 percent while at the same time their willingness to drive was in the 80 to 90 percent range. This was especially true for driving to or from work. As with work-related driving, the willingness to drive to school or to an important appointment decreased only if road conditions were snow-covered and compacted or showed one intermittent wheelpath.

Winter road conditions have a greater impact on driving that is more discretionary such as shopping or late afternoon school activities (practices, sports, workouts). This was true in both Greater Minnesota and the Metro area.

Greater Minnesota drivers' willingness to drive under poorer road conditions increased as the day passed. For the late afternoon, the willingness to drive on snow-covered and compacted roads for shopping purposes doubled from that measured for 7 a.m. to 9 a.m. However, even though acceptability for these poorer conditions increased, willingness to drive levels did not.

It is notable that in the Metro area drivers are more willing to drive on four-lane divided highways than on Interstate highways for discretionary driving under similar winter driving conditions. This may be for reasons other than the road condition, such as anticipated delays that might be experienced on Interstate highways due to traffic volume, or because of a greater feeling of safety on four-lane divided highways due to slower speeds.

If a snowfall occurs in the Metro area during the workday, drivers who otherwise leave for home between 4 p.m. and 6 p.m. will leave at their usual time. Similarly, many drivers who otherwise leave for home later than 6 p.m. will also leave at their usual time. If road conditions are either snow-covered or characterized by intermittent wheelpaths, most of these drivers will be uncomfortable driving and will rate the roads as unacceptable. However, these same drivers remain willing to drive under these conditions.

Recommendations

Because the greatest impact on improving road acceptability is to clear two lanes, MnDOT should consider clearing all road classes to this level before going back to upgrade the road condition to fully bare. While fully bare roads are always rated as the most acceptable, those with two cleared lanes, centerline covered with or without edge lines showing, are most often considered to be almost as acceptable as the fully bare roads and more acceptable than those with intermittent wheel paths.

Greater Minnesota

For the greatest impact on acceptability in the Greater Minnesota area, four-lane divided highways should have two cleared lanes, centerline covered with edge lines showing, by 6 a.m. Greater Minnesota two-lane roads (two cleared lanes, centerline covered without edge lines) should be cleared to a high level of acceptability by 7 a.m. to 9:00 a.m.

The increase in road acceptability for two lanes cleared on two-lane roads far exceeds the increase in acceptability from improving two lanes cleared to fully bare on four-lane divided highways. Therefore as the day passes, MnDOT should focus on providing two-lane roads with two lanes cleared, centerline covered with or without edge lines showing, before clearing four-lane roads to a fully bare state.

Metro Area

In the Metro area, both Interstate highways and four-lane divided highways should be cleared to two lanes with centerline covered and no edge lines showing by 6 a.m. Two-lane roads should be improved to this level by 7 a.m. to 9 a.m. for greatest impact on acceptability.

Levels of acceptability for all winter driving road conditions worse than fully bare on Interstate highways are far below the acceptability level for fully bare. Therefore in the late afternoon (4 p.m. to 6 p.m. 1 to 3 h after a snowfall has ended), Metro area Interstate highways should be fully bare if at all possible. On four-lane highways, MnDOT should strive to have two lanes cleared, centerline covered with or without edge lines showing; in acceptability levels these conditions are closest to fully bare for four-lane divided highways. On two-lane roads, anything better than one intermittent wheelpath is a decided improvement for the late afternoon drive-time.

Vehicle Speed and Flow in Various Winter Road Conditions

Carl-Gustaf Wallman

Continuous measurements of traffic and weather variables were undertaken at five road sites in central Sweden during the winter of 1998–1999. Visual observations of the state of the roads were made at the same time. Traffic measurements, with the vehicles grouped into three categories, included vehicle speed and flow. Data were aggregated as average values per hour. Weather data were gathered from Road Weather Information Systems stations of the Swedish National Road Administration close to the observation sites. The data included precipitation (rain or snow), intensity (mm/h), risk of slipperiness due to hoarfrost and other similar conditions, air temperature, road surface temperature, wind force, and wind direction. Observations were made on weekdays from 6 a.m. to 8 p.m. Observational frequency of road states varied from twice per day to once per hour depending on the situation. The road states were classified into one of 18 categories depending on road surface characteristics. A new data analysis method was developed whereby traffic data for hours of normally similar traffic conditions were compared. Any observed differences could therefore be assumed to be associated with different weather or road conditions. The method takes into account daily, weekly, and seasonal variations in speed and flow. The analysis resulted in data for the average speed and flow for any particular road state compared with averages for bare road conditions. For speed, significant, systematic, and plausible differences were established. Road surface conditions, however, were shown to have no systematic influence on traffic flow, suggesting that weather is probably a more important factor.

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To meet drivers' needs for safety and accessibility, road networks must be kept in good condition. Pavement should be even and free of ruts, cracks, and other damage. To maintain good friction in winter, roads must be clear of ice and snow. However, with the limited resources available to road administrators, these goals cannot always be achieved, and priorities must be established regarding what actions to take when, where, and how. To optimize maintenance actions (or at least enable making sufficiently good choices), administrators use management systems that require an assessment of the effects of road conditions and maintenance efforts on road users.

Winter conditions imply snow and ice on the road surface, which lead to considerable socioeconomic consequences mainly as a result of increased accident risk, reduced accessibility, and increased vehicle cost. Environment is also affected primarily as a result of salting actions. The relationship between weather, traffic, maintenance actions, and road conditions is illustrated in the Winter Model flowchart (Figure 1).

The Winter Model consists of submodels for assessing the state of the road, its effects and their appraisement, and road maintenance optimization. For some of the submodels, relevant variables and effect relations are known, but there are many areas in which far more knowledge is required, knowledge that can only be obtained by assiduous effort.

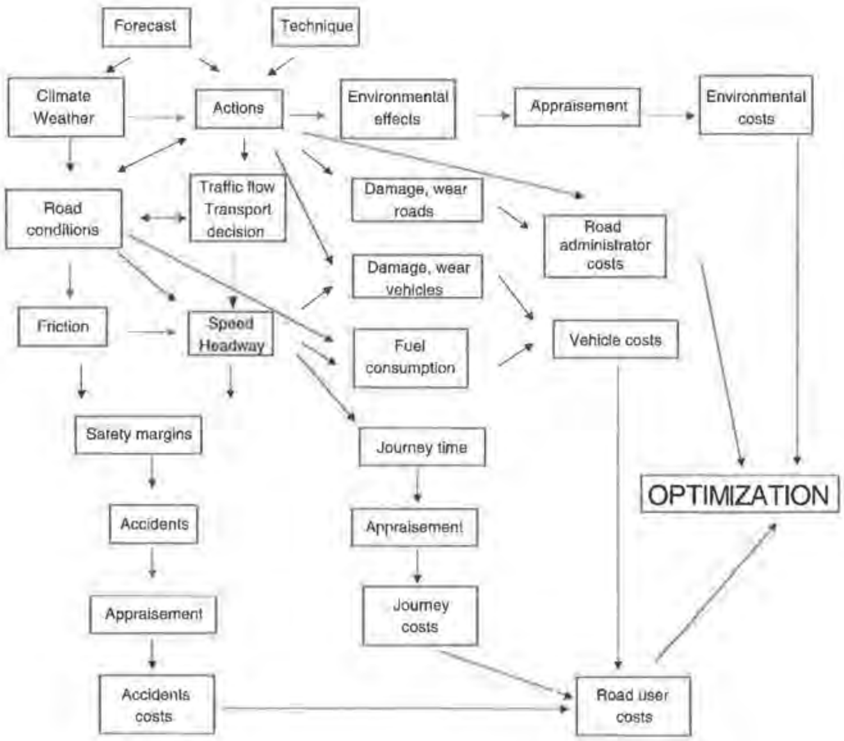


FIGURE 1 Winter Model for optimizing winter road maintenance: relation among different effects.

The most practical way to develop the Winter Model is to study the submodels individually. This approach takes into account the needs of the main sponsor of this project, the Swedish National Road Administration (SNRA), which is providing long-term financing for the project.

One important submodel, which is also useful alone, describes the relationship between weather, traffic, maintenance actions, road condition, and vehicle speed and flow, as shown in Figure 2.

The effect of roadway ice and snow on traffic speed and flow is not well understood, mainly because conditions vary and may exist only for a short period. A successful assessment of these effects calls for very close monitoring of the road state and the weather. The winter road surface state cannot be described by one uniform condition; a number of ice and snow states for the road have to be defined. In addition, the difficulties of measuring vehicle speed and flow are considerable. In Sweden, traffic measurements are

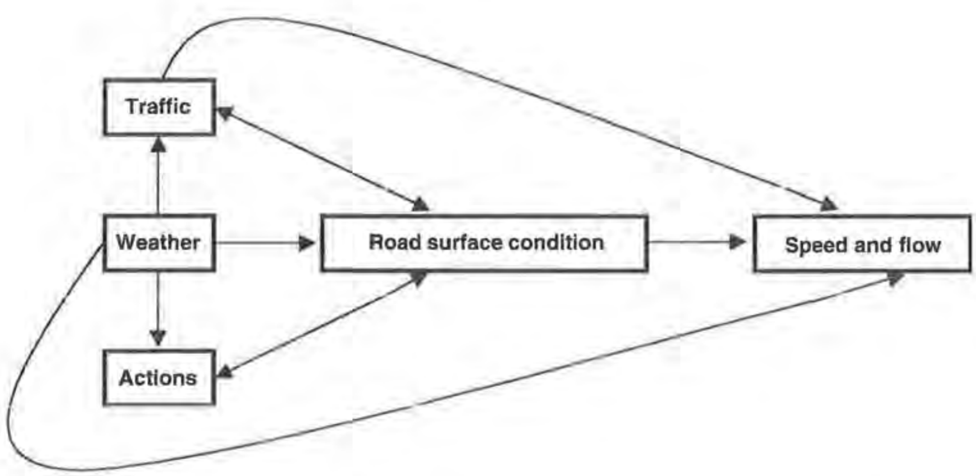


FIGURE 2 Relation among traffic, weather, actions, road surface, and speed and flow.

generally carried out using rubber tube sensors, which are not suited to winter conditions. Until now, the quality of data has been too poor to support any detailed analysis.

HYPOTHESIS

In winter, the road surface may be covered with snow and ice. This cover is subject to influence by the weather, maintenance measures, and traffic. The properties of the ice and snow cover (such as its appearance, extent, texture, and friction) influence drivers' behavior. This effect can be measured by variations in vehicle speed and flow. Other important factors influencing driver behavior are precipitation and visibility.

Measuring vehicle speed and flow while simultaneously monitoring weather and road surface conditions will yield data that can be used to develop reliable models for estimating effects.

METHOD

Selection of Sites

The goal of this project is to study representative roads all over Sweden, an undertaking that will last several years. For the first year (represented in this paper), the intention was to choose sites where there existed a high possibility of frequent icy and snowy road conditions so that data capture routines, database management, and analysis methods could be tested. The roads were preferably to be nonsalted and have fairly low traffic volumes.

For practical and financial reasons, the number of sites was restricted to five. All sites were two-lane roads located in central Sweden. Data describing the sites are shown in Table 1.

Traffic Data

The SNRA's standard equipment for measuring traffic data was used for this project. However, to ensure good performance under any road surface condition, standard tube sensors were exchanged for inductive loop sensors. There was a loss of accuracy in vehicle classification, but this was a minor disadvantage compared to the added reliability of the system. Vehicle speed and flow were recorded as average hourly values. Three vehicle categories were distinguished: private cars, trucks with no trailer (including buses), and trucks with trailer. Data were collected separately for the two road directions.

Weather Data

SNRA has about 660 Road Weather Information Systems (RWIS) stations across Sweden. On average there is one weather station per 150 km of national road. There were no significant obstacles in finding suitable stations for each of the different road categories involved in this project.

Raw data from RWIS required only light processing. The data were acquired hourly by air temperature, road surface temperature, precipitation quantity, wind direction, wind force, and weather situation (fair, rainfall, snowfall, blowing snow across the road, or risk of slipperiness due to freezing rain or frost).

Traffic and weather data were transmitted by cellular phone to SNRA and forwarded to the National Swedish Traffic and Transport Research Institute (VTI) via the Internet.

Road Surface Observations

Two observers were trained for each observation site. Depending on the weather and road surface conditions, the observers were to note road conditions from twice per day to once per hour. The state of the road was broadly defined as either changeable or steady. Changeable conditions prevailed when there was precipitation, when the road was wet or moist or covered with soft snow, slush, hoarfrost, or black ice. Under these circumstances observations were made every hour (from 6 p.m. to 8 a.m.). Steady conditions prevailed in fair weather and when the road was dry and bare, or if the road was covered with hard-packed snow or thick ice. In the case of a steady state, only two observations per day were necessary.

TABLE 1 Data for the Five Sites, Winter 1998–1999

	Width (meters)	Speed limit (km/h)	AADT	Skid-control
Site #1	8.8	90	2000	Salt
Site #2	9.0	90	3130	Sand
Site #3	7.0	90	2000	Sand
Site #4	7.0	70	2680	Sand
Site #5	8.5	110	1000	Sand

Observations were made on only one lane of road. Five separate strips on the lane and two on the shoulder (as shown in the roadway cross section in Figure 3) were observed. More specifically, these strips were the outer and inner halves of the shoulder, the edge of the lane, the right rut, between the lane ruts, the left rut, and the middle of the roadway. Each strip was 100 m long. During each roadway observation the average condition of the 100-m strips were recorded. If the width of the shoulder was less than 1 m, no notes were taken for it. Observations were made from right to left as seen from the driving direction.

The strips were described in terms of bare pavement (dry, moist, or wet) or different kinds of snow or ice (soft snow, slush, hard-packed snow, thick ice, black ice, or hoarfrost). The thickness of soft layers was also measured, as was the width of ice or snow strips between the ruts and along the middle of the road.

Data Processing and Analysis

A custom-made database manager was developed for loading traffic, weather, and observed data into the database. The observed data were processed before loading, which involved applying a set of rules to categorize the conditions of the 100-m strips into 18 specified road states. Essentially these states were bare surface (dry, moist, or wet), hoarfrost, black ice, hard-packed snow, thick ice, soft snow, and slush. Rutted conditions were also defined. In the ruts the pavement must be visible and must be described as either bare pavement or black ice. Outside the ruts there were other kinds of ice or snow layers. The specified states may be viewed as a standard description of winter road surface conditions in Sweden and Norway. The traffic data were prepared before being loaded into the database by calculating the average speed for both directions and summing the two flows.

Instead of relying on the usual regression analysis, a new method of evaluation was developed. The underlying concept was to match pairs of hours in which only the weather and surface conditions differed. Each member in a pair should have close to equal traffic conditions (speed level and number of vehicles). Consequently, daily, weekly, and seasonal variability of traffic flow had to be taken into account. Daily variation was accommodated by comparing one particular hour with the same or adjacent hours on another day (e.g., the 9th hour on a Tuesday would be matched with the 8th, 9th, and 10th hour on a following Thursday). The weekly variation was considered by combining comparable days, such as Mondays and Thursdays, into one group; designating Fridays as their own group; and combining Saturdays, Sundays, and holidays as a last group. Seasonal variation was accommodated by limiting the time span for comparisons to a maximum of 14 days before the current day. The variability of the traffic was assumed to be applicable only for levels of speed and flow; accordingly, the differences between two different weather and surface conditions are presumed to be the same throughout the season. Each site was analyzed separately.

Theoretically, 153 different pairs are possible. Each member is primarily identified by its surface condition. A number of other attributes are attached to the member: date, hour, weather conditions, average speed and number of vehicles in each vehicle class, and a code for daylight or darkness. Briefly, the statistical analysis comprised a regression analysis of the result of all matched pairs and relating the differences to the speed at dry, bare surface conditions. Before performing the analysis, the data had to be prepared using sophisticated mathematical and statistical methods to eliminate redundant matches and weight data of members joined by more than one member. This statistical method will soon be published separately.

Results

The output from the analysis was hourly mean speed and flow for wet, icy, or snowy road surface states, expressed as divergences from the dry, bare surface condition. An

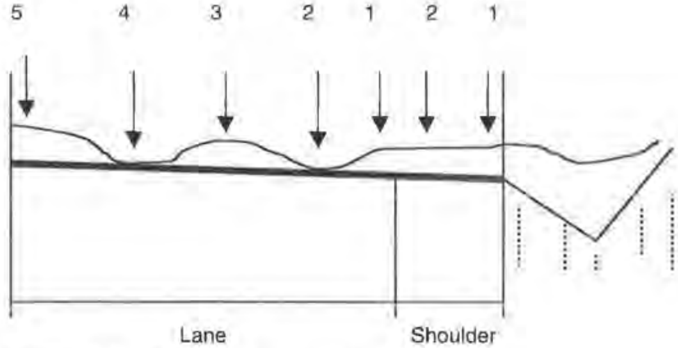


FIGURE 3 Observed strips on the roadway.

TABLE 2 Average Speed at Dry, Bare Surface Conditions

	Private cars	Trucks with no trailers	Trucks with trailers
Site #1	100.1	90.7	82.5
Site #2	98.6	89.6	83.9
Site #3	93.4	83.4	81.0
Site #4	77.3	78.8	74.4
Site #5	101.0	91.2	82.3

estimate of speeds at dry, bare states is shown in Table 2 as a 24-h average.

Results for the different road surface states are shown in Tables 3 and 4 for speed and flow, respectively. The tables comprise mean values and 95 percent confidence intervals for private cars. R stands for rutted conditions, B denotes bare surface in the ruts, and BI denotes black ice. "Hard" means that hard-packed snow or thick ice surrounds the ruts, and "Soft" indicates soft snow or slush. Finally, "Misc" (for "Miscellaneous") means that both soft and hard layers were found outside the ruts.

Speed

Some results were based on few observations, as can be seen by the large confidence intervals. However, most of the speeds at the different states of the road showed significant differences from the speed at bare road surface. There is great variation among the mean values; however, clear tendencies toward systematic divergences between different winter conditions can be noticed. For example, soft snow or slush generally results in greater speed reduction than black ice or hoarfrost. Rutted conditions with

TABLE 3 Speed Divergences from Dry, Bare Surface Conditions (Significant Values in Boldface)

Surface	Site #1	Site #2	Site #3	Site #4	Site #5
Moist	**-0.9 ± 0.9**	**-3.7 ± 1.3**	-1.1 ± 2.0	**-1.6 ± 1.2**	4.6 ± 7.9
Wet	**-3.0 ± 0.9**	**-4.1 ± 1.6**	**-3.5 ± 3.5**	0.2 ± 0.8	**2.6 ± 1.9**
Hoarfrost	**-7.3 ± 3.7**	-2.4 ± 3.3			-3.7 ± 13.6
Black ice		**-4.5 ± 1.2**	**-7.9 ± 2.7**	**-1.3 ± 0.5**	**-5.8 ± 2.1**
Hard snow	**-14.0 ± 3.0**	**-16.0 ± 3.1**	**-9.4 ± 1.7**		**-6.2 ± 3.3**
Thick ice					
Soft snow	**-12.5 ± 1.9**		**-7.9 ± 3.4**		
Slush	**-11.3 ± 1.9**	-4.3 ± 9.5	**-11.2 ± 8.2**		
R(B, Hard)	**-6.4 ± 3.3**	**-5.8 ± 1.4**	**-5.6 ± 1.3**	**-2.7 ± 2.4**	**-7.0 ± 5.6**
R(B, Soft)	**-5.9 ± 1.1**	**-7.9 ± 1.5**	**-2.0 ± 2.7**		0.3 ± 6.1
R(B, Misc)	**-2.1 ± 1.4**	**-1.4 ± 1.0**	**-1.8 ± 1.5**	-0.3 ± 1.3	**-7.5 ± 2.8**
R(BI, Hard)		**-7.2 ± 1.0**	**-8.0 ± 1.3**	**-2.7 ± 1.2**	**-4.5 ± 1.2**
R(BI, Soft)	**-5.2 ± 2.3**	**-10.6 ± 1.3**	**-9.2 ± 2.7**	**-3.4 ± 0.9**	**-7.4 ± 2.2**
R(BI, Misc)		**-5.2 ± 2.3**	**-7.9 ± 1.6**	**-3.6 ± 1.1**	**-3.1 ± 1.5**

TABLE 4 Flow Divergences from Dry, Bare Surface Conditions (Significant Values in Boldface)

Surface	Site #1	Site #2	Site #3	Site #4	Site #5
Moist	**11.9 ± 10.0**	−0.9 ± 12.0	0.4 ± 16.0	**35.6 ± 18.3**	−2.4 ± 23.0
Wet	**15.1 ± 11.0**	10.6 ± 15.3	**47.9 ± 28.2**	**26.7 ± 12.7**	**10.5 ± 5.4**
Hoarfrost	17.2 ± 43.5	−24.4 ± 30.3			7.6 ± 39.6
Black ice		**−27.0 ± 11.5**	**−30.3 ± 20.4**	**14.4 ± 7.1**	3.2 ± 6.1
Hard snow	33.6 ± 34.8	**53.8 ± 28.8**	**−16.2 ± 14.1**		1.3 ± 9.8
Thick ice					
Soft snow	**−36.2 ± 22.7**		**−42.5 ± 27.4**		
Slush	−15.7 ± 22.3	15.4 ± 88.5	−22.4 ± 78.0		
R(B, Hard)	−12.0 ± 38.5	−7.8 ± 13.1	**−30.0 ± 10.2**	21.7 ± 37.1	4.1 ± 16.4
R(B, Soft)	**12.9 ± 12.4**	12.6 ± 13.9	−2.1 ± 22.1		2.6 ± 17.9
R(B, Misc)	**16.6 ± 15.9**	**−27.0 ± 9.7**	**−44.4 ± 11.8**	−12.6 ± 20.5	**−8.4 ± 8.0**
R(BI, Hard)		**−32.0 ± 9.6**	**−38.7 ± 10.3**	**19.5 ± 18.6**	**−7.8 ± 3.4**
R(BI, Soft)	−14.1 ± 27.5	−4.2 ± 12.2	−11.7 ± 21.6	**27.4 ± 13.7**	−1.1 ± 6.5
R(BI, Misc)		**−26.0 ± 21.5**	−5.8 ± 12.9	**30.6 ± 16.7**	**−12.9 ± 4.2**

black ice in the ruts lead to greater speed reductions than bare surface in the ruts. Moist or wet surfaces are generally associated with only slight speed reductions.

The analysis lacks any estimation of the influence of weather conditions. So far this influence has been studied in only a couple of case studies (see the section on case studies below).

Flow

In Table 4, flow divergences are given as the number of vehicles per hour. (A better measure would be the ratio of the numbers at prevailing conditions and at bare surface conditions). Differences in flow do not appear related to surface conditions. It is thus concluded that road states have very little influence on the decision to make a trip, especially for the roads in this study, many of whose users are long-distance ski tourists. The weather may well prove to be a more important factor.

Case Studies

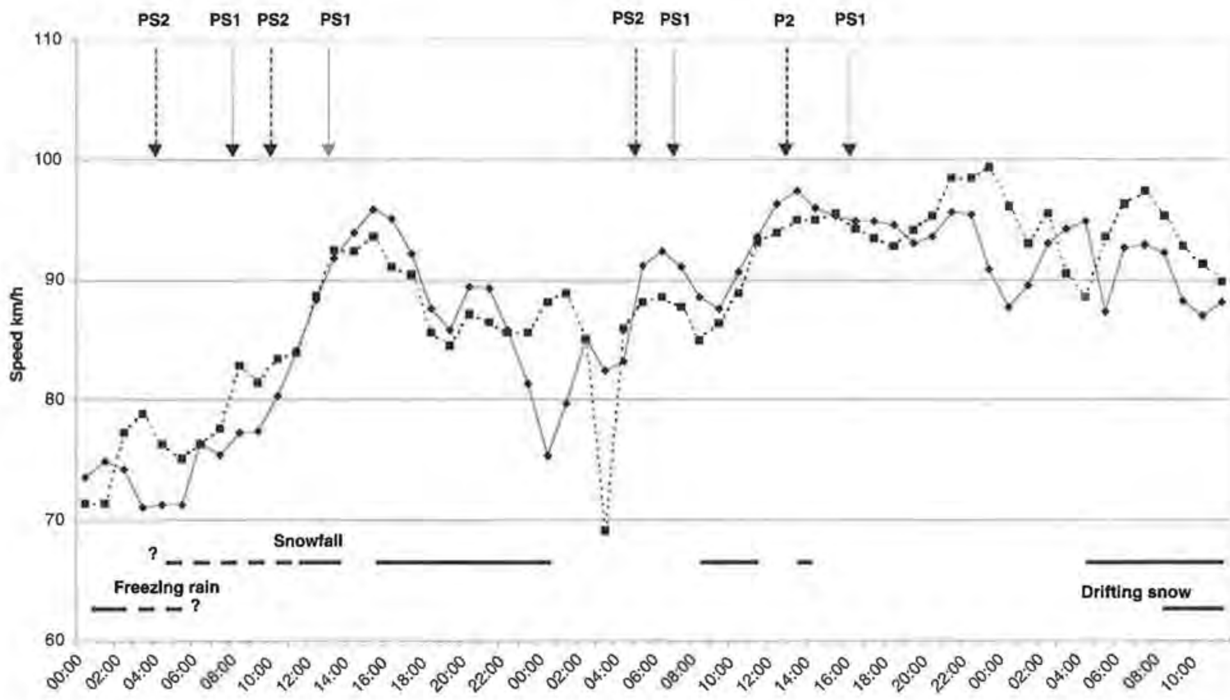
The data acquisition method and its close monitoring of traffic, weather, and road surface conditions meant that it was possible to follow the course of events during adverse weather conditions. This opportunity was twice utilized. One such event is shown in Figure 4. Here the observations of road conditions were extended so that 36 h of consecutive observations were obtained during the worst hours. The hourly average speed of private cars is plotted for each direction, together with weather data such as snowfall and blowing snow due to vehicle movement. Plowing and salting actions are also plotted in Figure 4 for the time they occurred at the observation site. It is possible to follow the speed adaptation to changing surface conditions, snowfall, visibility, snow control measures, and other factors.

To isolate the effect of weather, a small study was carried out for two successive days: the first had fair weather, and the second had snowfall as well as blowing snow due to vehicle movement. As can be seen in Table 5, significant speed differences in both directions were recorded.

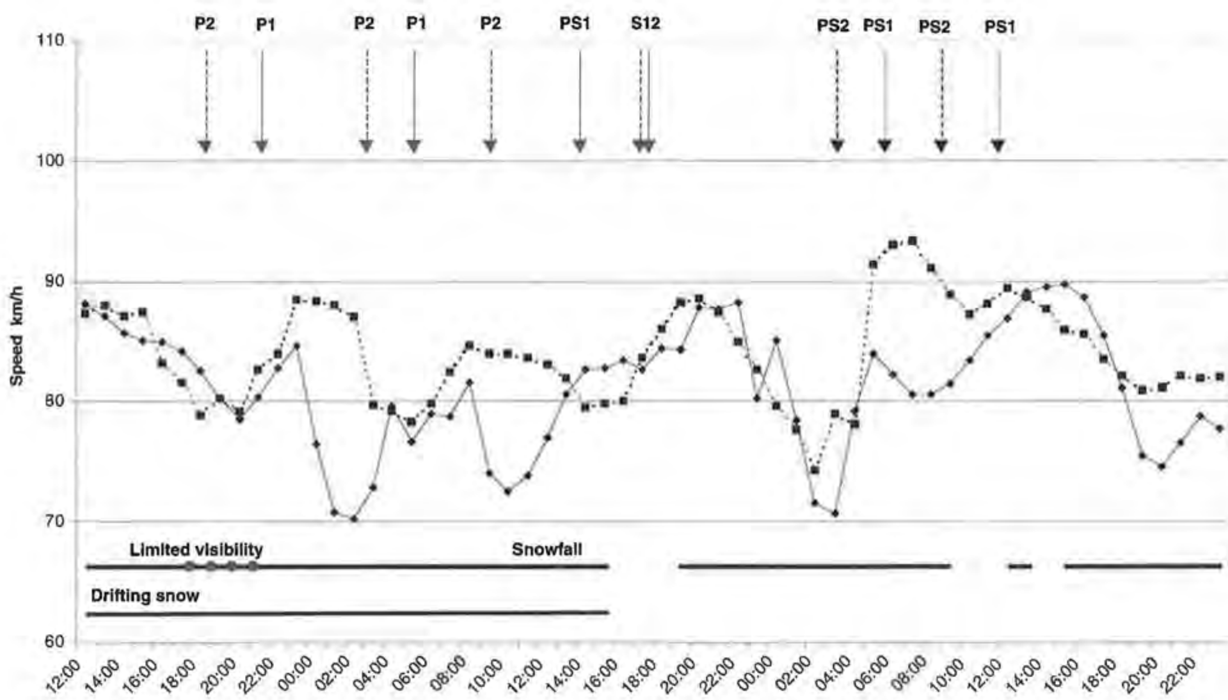
CONCLUSIONS

The methods for data acquisition, storage, and evaluation proved to work very well, thereby reinforcing intentions to successively extend surveys across Sweden.

The first results concerning speed reductions at different road states might, with some caution, be interpreted as follows:



(a)



(b)

Legend: Direction 1: continuous line, direction 2: dashed line
Px: plowing in direction x, Sx: salting in direction x
PSx: combined plowing and salting in direction x.

FIGURE 4 Hourly average speed at Site 1 for private cars during intense snowfall: (*a*) March 1–3, 1999; and (*b*) March 3–5, 1999.

TABLE 5 Weather Influence on Average Speed of Private Cars

Date	Hours	State of the road	Weather	Average speed	
				Dir. 1	Dir. 2
Feb 18 1999	9 – 18	Dry, bare	Fair	92.0	91.6
Feb 19 1999	9 – 18	Dry, bare	Snowfall, blowing snow	80.7	84.1

- The reduction for moist or wet bare surface is not unambiguous. For private cars the indicated reductions are 2 km/h for moist surfaces and 3 km/h for wet surfaces.
- For conditions with hard-packed snow, hoarfrost, or black ice, and rutted conditions with black ice in the ruts, the decrease for private cars is about 7 to 9 km/h.
- For conditions with soft snow or slush the corresponding value is 10 to 12 km/h.
- For rutted conditions with bare surface in the ruts, the corresponding value is 4 to 6 km/h.
- Trucks with no trailer generally have lesser speed reductions than private cars (about 2 to 4 km/h), whereas trucks with trailer reduce speed even less (by only 1 or 2 km/h).

ACKNOWLEDGMENT

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Expert System for Winter Road Maintenance

Magnus Ljungberg

The advantages and limitations of an expert system for winter road maintenance in Sweden, as well as how to create an expert system that is effective, are discussed. An expert system will support the decision making of the maintenance manager in real time. It is primarily intended for inexperienced maintenance management personnel. An effective expert system must render advice on what action should be taken, when it should be carried out, and, if necessary, how much and what type of chemical should be used on a road. Another important use for an expert system is the education and training of maintenance managers. Information for developing an expert system was gathered in part from literature studies, but the main informational source was interviews with experts. In-depth interviews with six experienced maintenance managers concerning winter maintenance activities took place during February, March, and April 2000. The interviews were based on examples in which present and forecast weather were given along with the time of day. The setting was the managers' actual area of operation along with the actual available equipment. Based on these examples, the managers were asked what action they would take and why. In order to obtain the best possible result, a follow-up was conducted, documenting what actions had been taken during conditions that matched the weather examples used in the interviews. A short discussion then took place as to why particular decisions were made. After the interviews were concluded, information was compiled and key parameters identified. Rules of best practice could then be formulated stating what action should be taken under conditions defined by temperature, wind, precipitation, and forecast. Actions were placed into three categories: plowing, sanding, and salting. Three types of salting were defined: dry, prewetted, and brine. The best practice rules also prescribe the correct amount of salt for spreading over a road. Preliminary results show that brine spreading is preferred over prewetted salt in most situations. Dry salt should never be used. For preventive salting, normal recommended amounts are 10 g of brine/m^2 (124 lb/lane-mi) or 7 g of prewetted salt/m^2 (87 lb/lane-mi). These best practice rules will later be incorporated into the expert system.

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To assess the possibilities and limitations of an expert system for winter road maintenance, a number of studies have been conducted. Although most of these studies were not primarily designed for assessing the suitability of an expert system, parts of the studies are nevertheless useful for that purpose.

Methodology

Assessing the suitability of an expert system for winter road maintenance is a part of a Ph.D. project entitled "Expert System for Optimal Winter Road Maintenance." The first study was a literature study of winter road maintenance, expert systems, and computer-based support systems for management of winter road maintenance (*1*). The literature study revealed that there are no expert systems currently in use anywhere in the world. One system, called VVEXP (*2*), was developed in Sweden at the beginning of the 1990s. A rule-based expert system that assisted maintenance managers with preventive salting actions, VVEXP was tested as a prototype during two winter seasons but was never fully developed. A survey (*3*) found that users were mainly receptive to the system; however, development was stopped because of financial reasons. Another system, the Deicing Anti-icing Response Treatment (DART) program, is under development in Canada and has been tested over two winters. The information available from the DART project is very limited, but the system appears to be a success and will be further developed.

Subsequent to the literature study, a problem description was developed using information from the literature study, interviewing persons experienced with winter road maintenance, and interviewing users of the finished expert system. These users were winter road maintenance managers with limited experience.

The number and geographical location of the experts, as well as the types of questions and techniques to be used for the expert interviews, were determined based on problem description results. The specific set of questions to be used for the expert interviews were developed based on actual weather situations occurring during January and February 2000.

The type of expert system to be used will be determined after the interview results have been processed. A rule base will then be created.

One significant conclusion from the problem description is that an expert system for winter road maintenance in Sweden has possibilities for success. Sweden already has an advanced support system for maintenance managers, but with an advanced expert system the country could make use of information that is difficult to employ today.

Problem Description

Background

In 1985 the Ministry of Communications gave the Swedish National Road Administration (SNRA), the Swedish Association of Municipalities, and the Swedish Road and Transport Research Institute (VTI) the task of creating a detailed research program with the goal of reducing the negative effects of salt in winter road maintenance practices without reducing traffic safety. The research program, MINSALT (*4*), was carried out from 1985 to 1991 and resulted among other things in the development of new methods and strategies for limiting the negative effects of salt applied to roads to reduce their slipperiness. The main findings of the research program were that (*a*) salt should be used preventatively (i.e., before slipperiness occurs) and (*b*) prewetted salt or brine should be used on roads. The program estimated that employing its proposed methods and strategies could reduce salt consumption by 20 to 40 percent.

For reasons partly related to a change in winter road maintenance procurement, the strategies proposed in MINSALT have not been fully implemented. In practice, winter road maintenance methods and strategies have remain unchanged despite the knowledge gained from MINSALT.

Sweden now has full competition for all road maintenance activities (personal communication, G. Henrysson, 2000). The Swedish state road network is divided into 144 road maintenance areas. A contractor is responsible for maintenance activities in each area during the contract period, which usually runs 3 to 6 years. A number of private contractors and the SNRA Produktion, which is handled as a private contractor, have been awarded contracts since the start of competitive bidding in 1993. SNRA Produktion is the largest contractor in winter road maintenance and has approximately 75 percent of the market.

Competitive bidding means that the contractor for a maintenance area can change at the next procurement. This in turn means that detailed knowledge about a particular area can be lost. An expert system, however, can assist the new contractor in expeditiously acquiring area knowledge.

Traffic safety analyses show that the number of accidents varies very little on main roads during winter, despite the weather during this same period varying from very cold to very mild. However, the amount of salt spread over winter roads varies greatly, without any measurable differences in traffic or traffic safety.

During winter there are occasions when road maintenance has failed, resulting in serious accidents. During two winter seasons, from 1993 to 1995, a failure study on winter road maintenance was conducted (*5*). For the study, the SNRA commissioned the VTI to determine, under conditions of failure, what actions the maintenance operator had taken and why the road surface condition was poor. Police-reported accidents were used as a basis for identifying failure conditions. However, the information gathered to answer the key questions was insufficient. But one observation indicated that on a remarkably high number of occasions the salting actions were carried out too late (i.e., after the road had become slippery) although failure conditions could have been foreseen with the information available from the Road Weather Information System (RWIS).

In the light of such circumstances, there exists a need to review strategies and methods in order to provide better support for the road authority concerning strategy selection and for the maintenance manager (foreman) concerning the choice of method.

With an expert system or decision support system, choosing the most appropriate and efficient strategy, action, and time can be made easier, thereby helping to reduce the amount of salt spread required while also lowering the risk of winter road accidents.

Goal

The goal of this project is to develop an expert system that will aid the maintenance operator in choosing the right winter road maintenance method, at the right time, for different road classes, traffic volumes, weather conditions, road surface conditions, and other factors. The expert system should also contribute to SNRA goals for winter road maintenance. This means that traffic safety should be increased while salt consumption and cost are reduced.

This development of an expert system will focus on choice of method, spreader type, material type and quantity, and other factors, all at the winter road maintenance operator level.

Decision Situation Today

Maintenance area managers in Sweden are responsible for ensuring that the roads they oversee meet the maintenance standards prescribed in the procurement. A maintenance area in Sweden normally consists of 500 to 1000 km of roads. The roads are categorized into six classes of maintenance standards, depending on traffic volume and importance.

The road surface standard is prescribed by a set of rules known as Drift 96 (6), which is maintained by the SNRA. The requirements for action times, friction levels, and snow depth vary depending on the class of maintenance standard for the road. Figure 1 is an excerpt from the Drift 96 rules for one standard class.

The number of maintenance vehicles available to the maintenance manager may vary between different areas depending on the distribution of standard classes in the areas. Areas containing a large proportion of roads with high traffic volumes may have as many as 20 vehicles equipped with salt spreaders, while an area with primarily low-volume roads may have as few as 2 or 3 salting units. The number of vehicles used for snow clearance does not vary greatly. Twenty to thirty snow-clearing units is normal. It should be noted that in the most northerly part of Sweden no salting is carried out.

The available information on which a maintenance manager bases his or her decisions consists of weather information from VViS, the Swedish road weather information system, and SMHI, the Swedish Meteorological and Hydrological Institute. VViS measuring stations are placed along the Swedish road network (7). There are currently about 650 stations, an example of which is shown in Figure 2. In the figure, "Vindriktning" refers to wind direction, "Vindhastighet" to wind speed, "Nederbörd" to precipitation, "Temperatur/fuktighet" to temperature/humidity, "Elektronik/CP" to electronics, "Fryspunkt" to freezing point, and "Yttemperatur" to surface temperature. The most important weather-related parameters measured by the stations from the standpoint of a maintenance manager are as follows:

- Road surface temperature;
- Air temperature;
- Dew point;
- Precipitation, type;
- Precipitation, intensity;
- Wind, force; and
- Wind, direction.

Because the VViS presentation is Internet-based, maintenance managers can access the information from anywhere. A typical VViS screen showing different station locations is shown in Figure 3. Figure 4 shows the temperature information that is available at each station. The x-axis denotes the time of day for a 24-h day, and the y-axis represents the temperature in °C.

From SMHI, the maintenance manager receives weather prognoses in both text and pictures. Satellite images, radar images, and precipitation forecasts are also

Standard Class A2 (8000–16000 AADT)

The driving lane shall:

- During snowfall and up to four hours thereafter not have a greater snow depth than four cm of loose snow or two cm of slush
- Continuously be salted during rain that causes slipperiness
- Be free from ice within two hours after the rain that caused the slipperiness has stopped
- When there is no precipitation, during other times than stated above, be free from snow and ice

FIGURE 1 Excerpt from Drift 96 rules for winter road maintenance (6).

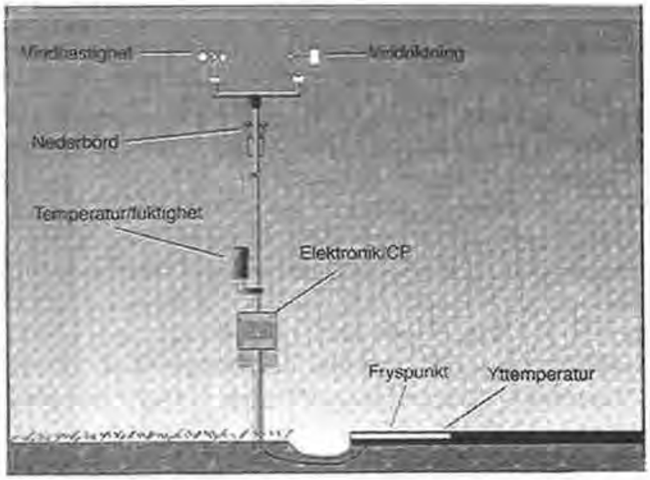

FIGURE 2 Swedish RWIS station (8).

available. The satellite pictures are used to predict the movement of fronts and determine whether or not cloud cover is dissipating. Radar images are used to predict the occurrence and intensity of precipitation. A satellite image is shown in Figure 5 and a radar image in Figure 6. (The white lines in Figure 6 represent boundaries. Precipitation is represented by colored pixels of green, yellow, and red, which appear as the lighter-colored areas in this black-and-white representation.)

It is difficult for a beginner to manage all this information, and making the right decision concerning the appropriate action to be taken, and when, is no easy matter. In addition, conditions within an area also vary as a result of differences in topography.

Other Factors

Besides weather information, data for the proposed expert system consist of information about the area, including available vehicles and equipment. A temperature profile for all roads in the area is also included. At Gothenburg University, a local climatological model (LCM) that can determine temperature variation along a stretch of road has been developed (9).

Although many experienced persons are employed in winter road maintenance, none can be regarded as a leading expert because conditions vary among different areas and locations. In addition, decisions about the same problem may not be the same. Acquiring knowledge from experts is therefore problematic. On the other hand, knowledge about winter road maintenance is relatively stable over time. As a result, the knowledge database only has to be updated once a year, primarily because of changes in SNRA rules (Drift 96).

For an expert system to be accepted by the user, it has to provide suggestions that the user does not discover on his or her own or that is already in use. For example, when salting takes place today, the whole road network in an area is salted because measurements from RWIS stations

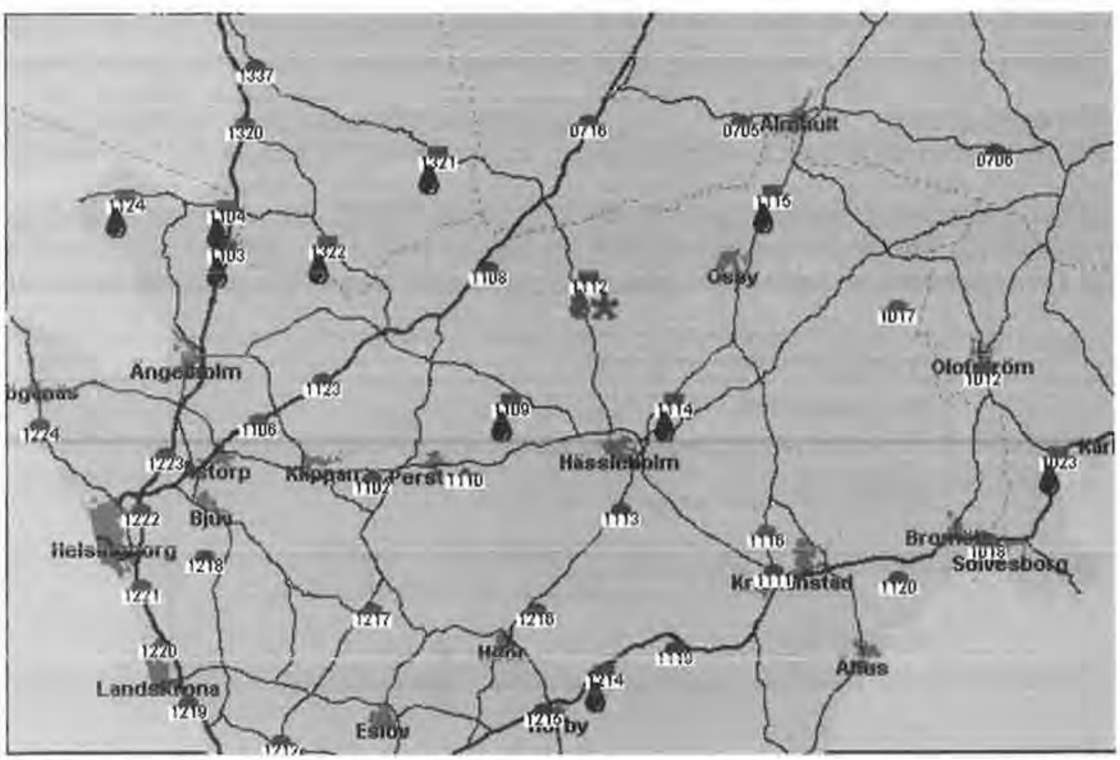

FIGURE 3 VViS screen capture (source: SNRA).

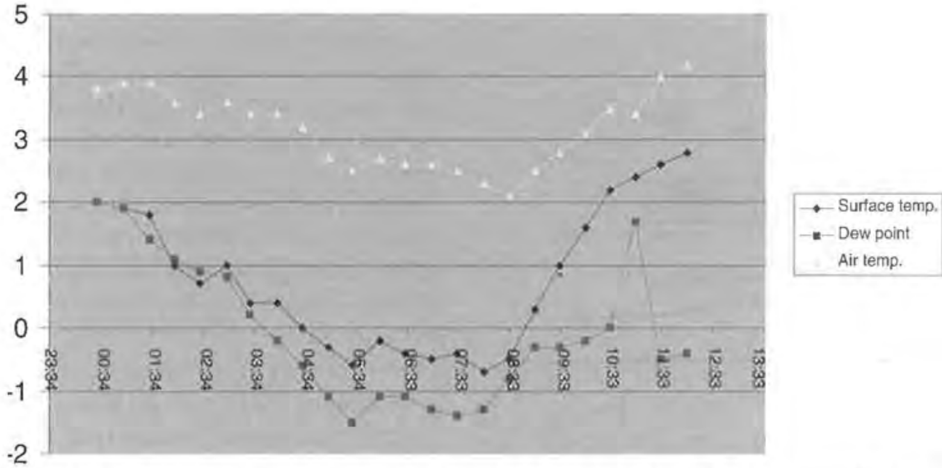

FIGURE 4 Temperature measurements from RWIS Station No. 646, February 11, 2000 (source: SNRA).

do not represent stretches of road between stations. With information from an LCM and an experienced maintenance manager, the expert system could recommend actions on those stretches where information is otherwise absent.

Proper assessment of the amount of residual salt on a road surface is an important factor for the success of an expert system. Although residual salt is difficult to measure, a theoretical model is under development (*10*), and measurements of residual salt have been carried out as part of this project. The results of these measurements are shown in Figures 7*a* and 7*b*. (In Figure 7*b*, "Prewetted" and "Slurry" are indicated by the same line.) If this measurement model were implemented in an expert system, the effectiveness could be substantially increased.

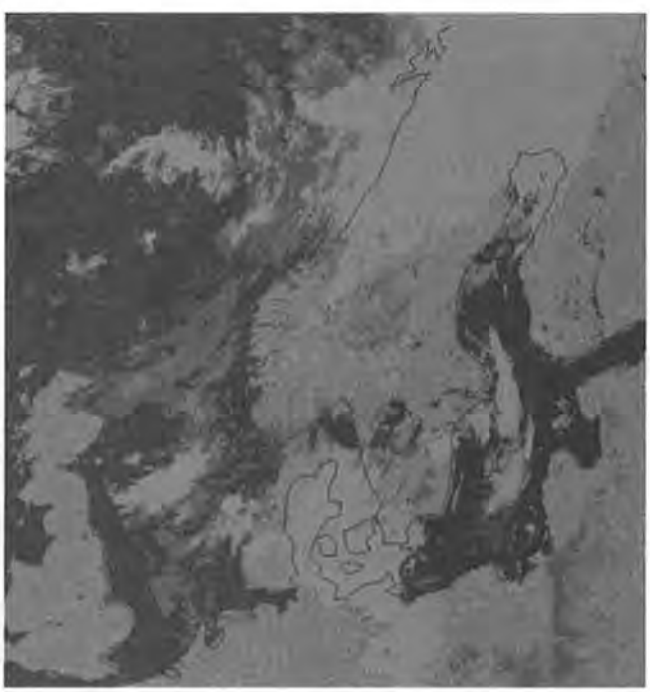

FIGURE 5 Satellite image of Sweden showing cloud cover (source: SMHI).

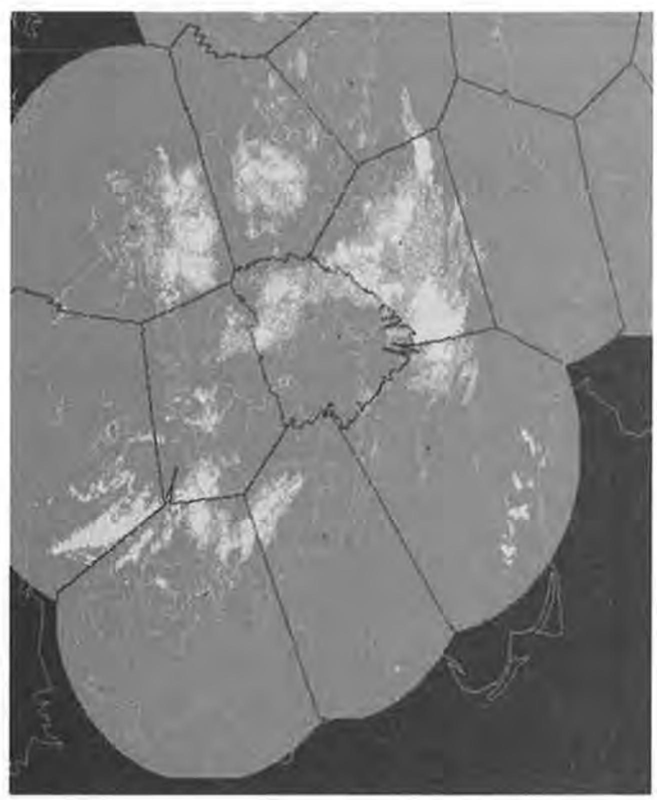

FIGURE 6 Radar image showing precipitation (source: SMHI).

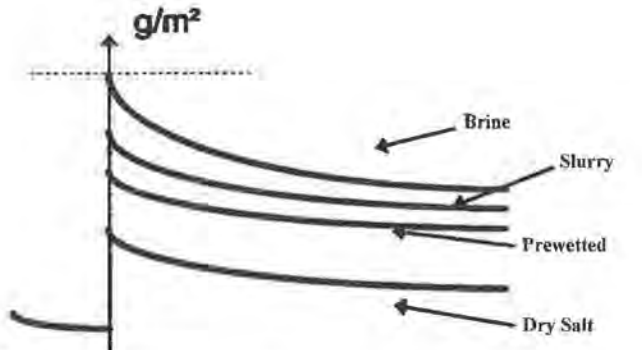

FIGURE 7 Residual salt measurements (*10*): (*a*) on a wet surface, (*b*) on a dry or damp surface.

Knowledge Acquisition

To determine the level of demand for an expert system and to identify situations where such a system would have the greatest impact, five would-be users of the completed system were interviewed. The users were new to the position of winter road maintenance manager (foreman) and had limited experience in the road maintenance field. The interviews were recorded and were based on a questionnaire concerning the managers' working situation and decision circumstances.

In selecting suitable experts for the interviews, a number of persons with extensive experience and wide connections in their industry were asked to recommend persons whom they considered to be experts in winter road maintenance. A criterion for selection as an expert was employment as a winter road maintenance manager (foreman) during the winter season the study was performed.

To obtain desired results from the interviews, it was important to follow a predetermined interview method. In *An Introduction to Knowledge Engineering* (*11*), Smith lists various methods for conducting effective knowledge acquisition interviews and provides guidance for the expert interviews conducted in this research.

A frequent problem encountered in making decisions on winter road maintenance is whether to perform an action immediately or to wait. It was therefore important to choose an interview method that took into account this problem. An introspective method, together with a retrospective method (*11*), was used. The introspective method presented the expert with an example of a situation where a decision was required. The expert was instructed to argue both for and against the decision that would be made. The retrospective method required the expert and knowledge engineer to discuss a decision after the actual decision was made.

Several other methods exist for interviewing for an expert system, including identifying extreme situations and documenting decisions based on them, and conducting studies in which the expert is observed at work. Drawbacks to using extreme situations are that such circumstances are inherently rare, and actions carried out during such situations are not paid for in the same way as in normal weather situations. An important drawback to on-the-job observations is that the reasoning behind decision making is not explored as well as with introspective methods. Another disadvantage is that identifying a variety of situations necessitates making observations over a long period of time.

Based on the results from interviews with five beginner road maintenance managers and discussions with six experienced managers, a number of weather examples were compiled for use during the expert interviews. The examples, which consisted of data from the Swedish RWIS, radar images, satellite images, and weather forecasts from SMHI, were intended to reflect the typical situation under which an expert would make a decision on winter road maintenance.

RESULTS FROM KNOWLEDGE ACQUISITOIN

General

Beginners and experts were equally receptive and cooperative during the interviews. Their answers appeared earnest and candid, and they did not hesitate to talk about subjects that could be interpreted as negative for them.

Not surprisingly, there was a knowledge difference between beginners and experts. The beginners had less knowledge about winter maintenance methods and equipment, and they were more uncertain than the experts in making decisions. This is a prerequisite for further development of the expert system.

Beginner Interviews

All beginners indicated a need for a decision support system. The following reasons for this assistance were identified:

- Uncertainty concerning where road slipperiness first appears in their area.
- Very little knowledge about different maintenance methods and their effects. (The amount of salt used by beginners varied less compared with that used by the experts.)
- The need for a reliable forecast of road surface temperatures at least four hours in advance so that preventive salting could be completed before road slipperiness occurs.
- A request for residual salt measurements.

Beginners indicated they did not require assistance with snow clearance and sanding; however, they indicated that the assistance of an extra maintenance manager (foreman) would be required during heavy snowfalls because of problems associated with keeping track of numerous snow clearing trucks and the large number of reports that have to be sent to the traffic information center.

In general, beginners indicated they were dissatisfied with their level of compensation for being on call during the winter season. They said they would not accept being on call were it not an obligatory part of their job. Most beginners said they felt the pressure of responsibility for accidents, as well as anxiety if they should fail to observe a situation in which slipperiness has occurred.

Two out of five beginners said they intend to give up working in winter road maintenance because of the heavy workload and pressures of responsibility.

Expert Interviews

The primary purpose of the expert interviews was to create a knowledge database of maintenance practices for use in compiling a rules-based best practice manual for winter road maintenance in Sweden. Rules will be based mainly on road surface temperature, dew point, precipitation, residual salt, and the amount of water on the road surface.

In most cases the experts agreed on situations that require some form of maintenance action. Recommended salt amounts varied among the experts and according to different situations. Even though all experts interviewed had extensive experience (an average of more than 15 years in the field) in winter road maintenance, the amount of deliberation behind salting actions, method choice, and potential method effects varied greatly.

In general, the experts strive to use as little salt as possible while maintaining the prescribed standard. There are three reasons for this goal:

1. Lower salt costs,
2. Lower environmental impact, and
3. Faster-drying road surfaces.

The only chemical used in winter maintenance in Sweden is sodium chloride (NaCl). Other salts or chemicals that could be used are either too expensive or have an excessively negative impact on the environment or on bridges. In this study, salt is defined as sodium chloride.

There are two different methods for spreading salt, defined by the type of salt use. One method uses prewetted salt, and the other employs brine. Dry salt should never be used, according to the experts, because it does not stay on the road (Figures 7*a* and 7*b*), and it is much slower than prewetted salt and brine. Prewetted salt is dry salt that is wetted with 30 percent by weight of brine at the time of spreading. Brine is a saturated 23.8 percent salt solution of salt and water and is the method preferred by the majority of the interviewed experts in most situations. The advantages of brine over prewetted salt are as follows:

1. Total salt consumption is lower.
2. The melting effect is faster.
3. Road surfaces dry faster, in part because of lower salt quantities.

The disadvantages of brine over prewetted salt are as follows:

1. Maintenance areas must have equipment for spreading prewetted salt, as brine is not suitable for use during heavy snowfalls.
2. If the road surface is very wet or precipitation is ongoing, there is a risk that the brine will be excessively diluted and the liquid will refreeze.

All new spreaders purchased by SNRA Produktion over the last 4 years are combined spreaders (personal communication, G. Henrysson, 2000). A combined spreader can spread both pure brine and prewetted salt.

For normal preventive salting on dry or nearly dry surfaces when light hoar frost is expected, the recommended spreading salt amount is 10 g of brine/m^2. If the maintenance area does not have any brine spreaders, the recommended amount is 5 to 7 g of prewetted salt/m^2.

If the road surface is wet, the amount of brine should be doubled, to 20 g/m^2, and the amount of prewetted salt increased to 10 to 15 g/m^2.

In some situations, some of the experts use as little as 5 g of brine/m^2 (62 lb/lane-mi) for preventive salting.

To reverse or prevent slippery road conditions at low temperatures (less than −10°C), very small amounts of brine (less than 5 g/m^2) or prewetted salt (2 to 3 g/m^2) may be spread.

If a snowfall is expected, it is important to spread salt before the snowfall begins in order to prevent the snow from bonding to the pavement. The amount of salt spread should be 20 g prewetted salt/m^2. If the road surface is dry and colder than −7°C, the road surface temperature is not expected to rise significantly, and the dew point is below the surface temperature, the risk of snow bonding to the pavement is small and salting should be avoided. During snowfall, the spreading of extra salt should be avoided.

Experts indicated no reservations concerning sanding. Over the last few years there has been a change in the type of material used. Earlier, almost all sanding was performed with sand fraction (0 to 8 mm with 3 percent added salt). Salt was added to prevent freezing in stockpiles. Today, most sanding is done with grit (2 to 4 mm).

The situation cited as most difficult by most of the experts, which therefore constituted a situation in which an expert system would be useful to them, was the sky clearing suddenly. When this happens, the temperature on the surface can fall several °C in an hour.

Another situation where the experts indicated they would want more information is when determining whether the amount of residual salt on the roads is enough or if extra salt is needed to prevent freezing.

Proposed System Design

There are a number of parameters that cannot automatically be read by the expert system: weather forecasts, satellite images, radar images, and surface moisture. To obtain this information, the system must ask the user for input. Based on results from the literature study, a decision has been made to construct an expert system that is rules-based, using forward chaining and induction.

A rules-based system was chosen because it makes possible the ability to follow the reasoning behind decisions. The system is therefore transparent and enables a fuller understanding, a critical element of this project. A system based on neural networks or on case-based reasoning could also have been chosen if a full understanding of the system had not been as paramount. [A neural network system would probably have been easier and quicker to build (*12*).]

Forward chaining is suited to the selected type of expert system because it resembles process management (*13*). Induction is used on the rule base to create a decision tree in which the most important parameters for making decisions in different situations are revealed.

Figure 8 shows the schematic design of the proposed expert system.

Timetable and Recommendations

Timetable

The knowledge-gathering phase of this project was completed in April 2000. Creation of the rules database took place between May and November 2000. A prototype expert system will be completed by January 1, 2001.

Recommendations

Results from interviews with winter road maintenance personnel show a clear need for an effective expert system. The interviews were also valuable in assisting with the development of the prototype system. The critical factor

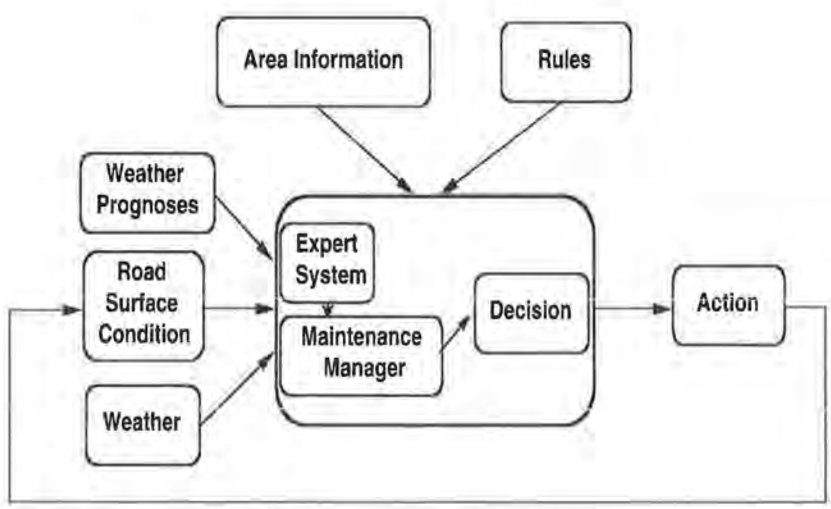

FIGURE 8 Schematic design of proposed expert system.

for success will be user acceptance. The system must be able to forecast situations in which slippery roads will occur and must also take into account possible amounts of residual salt. Recommendations provided by the system must be applicable to specific parts of a maintenance area, and the user's input to the system must be quite limited.

After testing of the system over one season, it should be evaluated to decide whether further development is warranted or if instead it should be abandoned. The evaluation should be performed as a user survey. A comparison with a similar maintenance area should be made to control for economic and salt consumption effects.

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Part 6
ENVIRONMENTAL MAINTENANCE

Long-Term Effects of Deicing Salt on the Roadside Environment

Part I: Forestry

Göran Blomqvist

The effects of winter road maintenance constitute a complex system of many interrelationships. One of these relationships is the effect of deicing salt on vegetation. Such effects are described in the form of a DPSIR (Driving force, Pressure, State, Impact, Response) model. According to the model, the need for transportation (D) leads to a roadside exposure to salt (P), which alters the state of the vegetation (S), thereby leading to different kinds of impacts (I), which may require some kind of response (R). The impacts of deicing salt on roadside vegetation are grouped into three spheres of interest: the public, landowners, and ecology. In Sweden, the Environmental Code requires that the Swedish National Road Administration work to understand how these complex systems operate and to take active measures to prevent damage to human health and the environment. This mandate requires knowledge of each DPSIR model element as well as the relationships between the elements. So far, research on this topic has resulted mainly in model indicators that cannot be used easily by road administrators. It is therefore of great importance to be able to assign adequate indicators to all levels of the model and to monitor these indicators on both a temporal and spatial scale that facilitates responding with the proper actions. To establish an environmentally sustainable winter road maintenance system, it is also crucial to establish the long-term tolerance limits of human health and nature as the base for salting strategies.

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During the winter season, both road safety and road network accessibility must be maintained to acceptable levels. The overall goal of Sweden's transport policy is divided into five subgoals or objectives.

1. An accessible transportation system,
2. High transportation system quality,
3. Traffic safety,
4. A good environment, and
5. Positive regional development.

Reconciling the first three goals with that of maintaining a good environment is a delicate matter involving conflicting interests.

Road administrators have had a long-term interest in the different impacts associated with winter road maintenance operations, and much effort has been spent on understanding the relationships between their actions and their effects on friction, speed, stopping distance, fuel consumption, corrosion, and traffic safety (*1*). But when developing an integrated management system for winter road operations, it is important to appraise all related consequences, including those on the environment.

Many studies have been conducted on the effects of deicing salt usage on the environment (e.g., vegetation, groundwater quality, and soil chemistry) (*2–7*). It has now become vital that the Swedish National Road Administration (SNRA) understand the integrated workings of the winter road maintenance system, including its component interactions, with a view toward protecting human health and the environment against damage or detriment. In fact the 1999 Swedish Environmental Code requires it. Under the same law, road administrators are required to implement protective measures and any other precautions that may be necessary to prevent or mitigate damage or detriment to human health or the environment as a result of any winter road activity or measure (SFS 1998: 808, The Environmental Code, Statute Book of Sweden).

The aim of this study is to describe, from the viewpoint of the road administrator, that part of the winter road maintenance system that involves the interrelationship between deicing actions and damage to vegetation and to present a model of that system, which will allow the involved components and processes to be identified and monitored.

Winter Maintenance Operations

Goals of Transport Policy and Environmental Law

In June 1998 the Swedish Parliament adopted a new transport policy on the basis of the government bill titled *Transport Policy for Sustainable Development* (SFS 1997:652, Statute Book of Sweden). The overall goal of the transport policy is divided into the five subgoals listed earlier: an accessible transportation system, high transportation system quality, traffic safety, a good environment, and positive regional development.

For the first objective, an accessible transportation system, accessibility is defined as the ease with which citizens, the business community, and public organizations can bridge distance in society.

The fourth objective, a good environment, is defined in the following requirement: "the design and function of the transport system will be adapted to the requirements for a good and healthy living environment for everyone, where natural and cultural environments will be protected against damage." Good management of land, water, energy, and other natural resources must be promoted. Also, the government bill on which the new transport policy is based establishes that long-term emissions goals be based on the tolerance limits of human health, environment, and nature (Government Bill 1997/98:56, Transport Policy for Sustainable Development).

The Swedish Roads Act (SFS 1971:948, Statute Book of Sweden) states that roads shall be held in a satisfactory state by maintenance and other measures. This mandate does not, however, overrule the requirements of the Environmental Code for the maintenance of roads (Government Bill 1997/98:90), which requires that its provisions be applied in such a way as to ensure that human health and the environment are protected against damage and detriment, whether caused by pollutants or other impacts, and that the best available technology be used in connection with professional activities (SFS 1998: 808, The Environmental Code, Statute Book of Sweden).

Winter Road Maintenance Effects

A key issue in the road management sector is ensuring that limited funds are spent to have the greatest impact within various applicable constraints (*8*). The winter road maintenance manager must achieve a balance among many considerations, including accessibility, safety, comfort, travel time, and the environment (*9*).

The system of winter road maintenance operations and their effects on traffic safety and road accessibility have been described by Wallman et al. (*1*). Maintenance measures are identified as the central component of the system. In the Wallman et al. model, each measure leads to a large number of interrelated effects. The influence of different winter road conditions on speed and traffic flow is discussed by Wallman in a paper in this proceedings. Winter road maintenance effects are divided into three categories in the Wallman et al. model: costs for the road user, costs for the road manager, and environmental costs (Figure 1). The most cost-effective measures are chosen after comparing the different costs (*1*).

Today the operating requirements of winter road management in Sweden are an aggregated function of road user costs and road manager costs (*9*).

Roadside Exposure to Salt

Deicing salt is used to prevent slippery conditions by forming a brine layer on the road surface that prevents snow and ice from bonding to the surface. In this deicing action system, vehicles play an important role by forming slush and then forcing the salt-laden slush off the road. Thus the dispersion of salt from the road is built

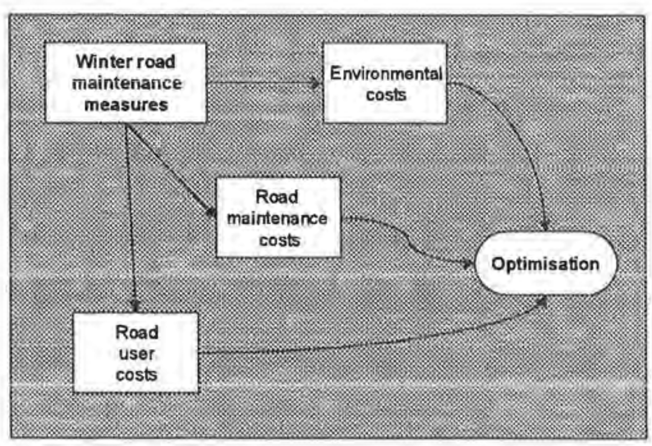

FIGURE 1 Winter maintenance operations system and effects [simplified after Wallman et al. (*1*)].

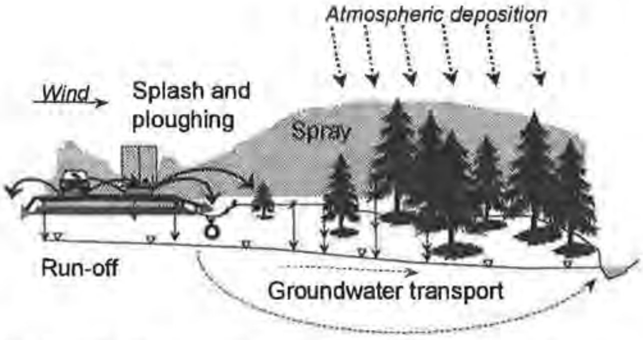

FIGURE 2 Conceptual model of salt transport mechanisms and salt pathways from the road.

into the system, as well as the exposure of the roadside environment to salt.

Deicing salt follows one or more of several pathways from the road, each of which is coupled to separate mechanisms that are regulated by a set of factors (*10*). The major mechanisms are runoff, splash, ploughing, wet spray, and dry crystal aerosols (Figure 2). The factors that regulate to what extent one or more of the mechanisms contribute to the total transport of salt from the road are traffic characteristics (type, speed, and intensity), road surface characteristics, salting management practices (amount, technique, and timing), meteorological factors, and other site-specific factors (including topography and hydrogeology).

A model or airborne salt deposition next to roads should be a function of the sum of each transport mechanism (e.g., splash and spray) and background deposition (Figure 3). The model variables should also be related to the factors regulating the transport mechanisms rather than a mere arbitrary function that can predict values within a specific range (*10*). The deposition pattern resulting from this model constitutes one aspect of the roadside's exposure to salt.

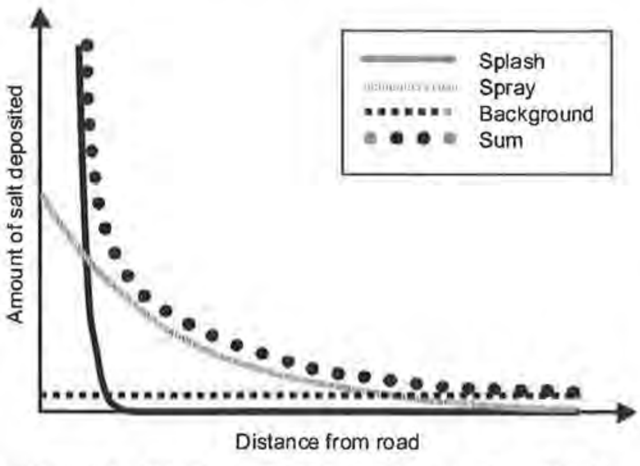

FIGURE 3 Model of total salt deposition in the roadside environment.

Environmental Effects, Damage to Trees

In many studies, damage to trees (both in field studies and under controlled conditions in laboratories) has been shown to occur both when salt is applied to the soil as well as when it is deposited onto the foliage (*2*, *3*). Symptoms in coniferous trees are often described as needle browning and needle loss (*11*). Some trees are able to compensate for the damage by producing new shoots, but when the damage is too great, this is not possible (*10*, *12*).

The consequences of this damage are many. One is the impact on biota in itself; another is the effect on the landscape. The impact of deicing salt on conifers is a result of a complex interplay of many causal relationships (e.g., loss of needles leading to lower photosynthetic capacity; osmotic stress through the increased amount of salt in soil water leading to inhibition of water uptake; and stress avoidance requiring energy expenditure). Most of these effects will in the end result in diminished growth of the tree stand and can also predispose the tree to damage from fungi or insects. Such effects have been described by, for example, Pedersen and Fostad (*11*). It is often difficult to distinguish among the different stress factors: one may have predisposed the tree to damage, another may have triggered the damage, and yet a third may have contributed to the actual killing of the tree (*13*).

The extent of tree damage is governed by a kind of dose-response function. In this case the dose is represented by salt exposure and the response by the degree of damage to vegetation. For some species the function has been suggested as S-shaped (Figure 4) in comparing the concentration of chloride in needle tissue to the extent of damaged needles (*14*). Many investigations have been conducted of the relationship between chloride amounts in needle tissue and the extent of visible damage symptoms. For example, comprehensive compilations have been published by Dobson (*3*) and Brod (*15*).

A field investigation in Sweden was performed as a potted plant experiment to check the extent and pattern of damage to two-year-old Norway spruce (*Picea abies*) seedlings in a deicing salt-exposed environment next to a

FIGURE 4 Theoretical functions of exposure to salt and susceptibility to salt damage give the pattern of damage in the roadside environment.

highway (*16*). The pattern of damage (Figure 5) was consistent with the theoretical curve in Figure 4. One should keep in mind, however, that the roadside environment is also exposed to many other stress factors (*6*).

Cost of Salt Damage to Trees

Some attempts have been made to calculate the cost of salt damage to trees. In a TRB Special Report (*2*) the cost was calculated as the cost of removing a dead tree and planting and maintaining a young tree in its place. On the other hand Vitaliano (*17*) represented the cost as the lessened demand for viewing a scenery of less aesthetically pleasing trees in areas heavily impacted by road salting. The two cost assessments focus on different aspects of the same problem: whereas the first considers the costs for mitigating the problem of dead trees, the second considers the costs of degraded landscape scenery. Both assessments are concerned with the costs of damage that has already occurred.

Randrup and Pedersen (*18*), however, focus on the costs of damage prevention, which they define as the estimated cost of replacing the soil of urban trees and of protecting trees using plastic-covered straw mats.

As concluded in a Finnish investigation (*19*), the main problem posed by deicing salt-induced damage is the discoloration of young Scots pine (*Pinus sylvestris*) trees. In an extensive Norwegian program studying the effects of deicing salt on soil, water, and vegetation, the most vulnerable species studied was Norway spruce (*11*). The most extensive damage reported in the Norwegian study was caused by the uptake of salt through the tree roots. In some states in the United States, 5 to 10 percent of roadside trees within 100 ft of the pavement edge along some sections of salt-treated primary highways exhibit signs of salt-related decline (*2*). In two Swedish studies (*20*), many sections along the primary highways exhibited damage to coniferous trees amounting to more than 70 percent of vegetation at the individual tree level.

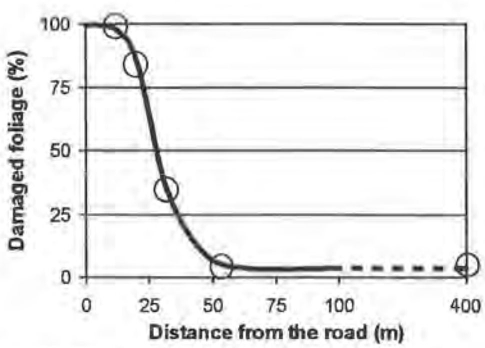

FIGURE 5 Pattern of damage to Norway spruce seedlings in a field case study.

Roadside trees and shrubs in Sweden have to some extent been removed as a road safety measure (Figure 6). This action also removes the symptoms of salt-damaged trees.

Forestry: A Process, Not a Steady State

Forestry should be thought of as a process rather than a steady state. While one effect of roadside exposure to deicing salt is a lower forestry yield, a potentially more significant long-term consequence may manifest itself during reforestation, as seedlings and young plants are much more sensitive to salt exposure than older trees. Reforestation may therefore be virtually impossible within a zone of up to several tens of metres from the road. In many places this zone extends beyond the road reserve area (i.e., the right-of-way boundary) and therefore may affect the land next to the road. If reforestation is not possible, the landowner is subjected to a forced change of land use (Figure 7), which will probably lead to different legislative possibilities concerning damage claims than would the impact of diminished growth along the roadside.

The economic consequences of these factors must be considered lest potential claims for damages by landowners come as an unpleasant surprise to road administrations.

System Description

The Swedish Environmental Protection Agency has established a system for the follow-up of national environmental quality objectives (*21*). The system uses defined indicators for each part of the process following the internationally accepted DPSIR (Driving force, Pressure, State, Impact, Response) model (Figure 8). Societal needs

FIGURE 6 Removal of roadside trees and shrubs to eliminate symptoms of salt-damaged trees and cutting and mowing of the roadsides to promote roadside biodiversity.

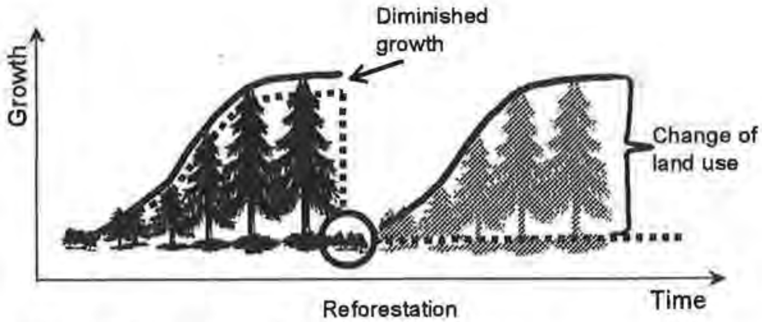

FIGURE 7 **Implications for forestry, seen as a process.**

and activities can be viewed as driving forces (D) that lead to a pressure (P) on the environment. This pressure may change the state (S) of some environmental components, which in turn can lead to impacts (I) on an area such as human health or nature. Finally, society will respond (R) in some way to combat the problem in one or several of the model's earlier stages (*21*).

Using the DPSIR model, the use of deicing salt and damage to vegetation could be described as follows (Figure 9):

- The driving force (D) is the transportation need of citizens and industry, formulated as subgoals (e.g., accessibility, quality, and safety). To be achieved, these subgoals require the use of deicing salt (*9*).
- The pressure (P) is the deicing salt that follows different pathways from the road to somewhere in the environment.
- The state (S) of the roadside vegetation is dependent on, for example, salt concentration on the plants, in the plants, in the soil, and in the soil water.
- The impacts (I) of the pressure-induced state are, for example, degraded landscape scenery, diminished tree growth (in the worst case forcing a change of land use), trees predisposed to secondary pests, and an altered species composition along the road.
- The societal responses (R) can influence all other levels of the system (D, P, S, I).

There are two elements in Figure 9 that are not included in the original DPSIR model (Figure 8). The first, indicated in the oval between driving force (D) and pressure (P), represents the activity induced by the driving force and causing the pressure. In this case the action is the deicing measure.

The other Figure 9 element not included in the Figure 8 DPSIR model comprises laws, directives, policies, regulations, and contract conditions (indicated in the box at the upper right of the figure). These are partly a result of societal needs (e.g., the need for transportation is manifested in some of the goals of the transport policy), but they can also be used by society as a toolbox for responding to all DPSIR model stages. Finally, this element also governs liability issues surrounding different impacts (I).

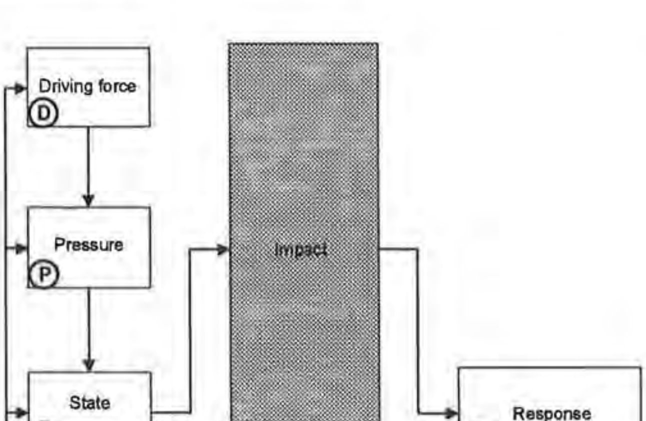

FIGURE 8 **DPSIR model.**

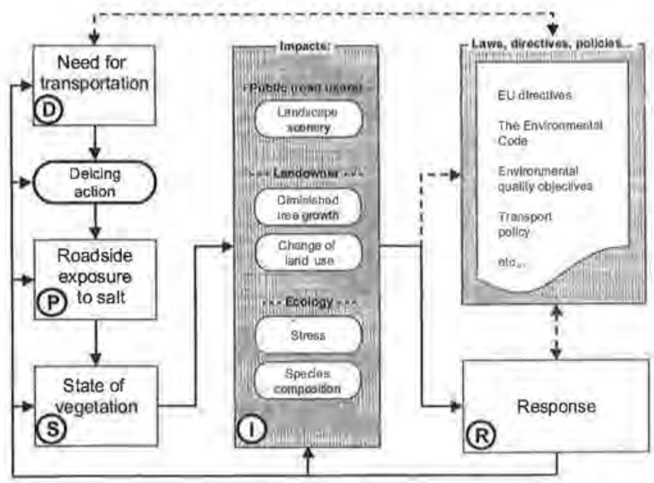

FIGURE 9 **Deicing actions and damage to vegetation as illustrated by DPSIR model.**

Each component in the DPSIR model (Figures 8 and 9) is connected by arrows representing the links and relationships between the components:

- The relation between the need for transportation (D) and deicing actions taken is governed by, for example, requirements in winter road maintenance operating rules (*9*) and available technology and methods.
- The relation between deicing actions and roadside exposure to salt (P) is dependent on such variables as the amount of salt used, salt type, speed and intensity of the traffic, road surface characteristics, wind speed and direction, and distance from the road (Figures 2 and 3).
- The relation between roadside exposure to salt (P) and the state of vegetation (S) can be described by a dose-response function (Figure 4) dependent on such variables as type of exposure, type of vegetation, ability to avoid or tolerate stress, and other contributing stress factors.

Discussion of Results

Responsibilities and Sustainability

Chapter 2:2 and 2:3 of the Environmental Code in Sweden (SFS 1998:808, The Environmental Code, Statute Book of Sweden) outlines the requirements of having knowledge of the impacts of one's activities and implementing protective measures in order to prevent impacts on human health and the environment. In the instructions for the SNRA the government charged the SNRA as the representative of the state with overall responsibility for the development of and developments within the road transport system (SFS 1997:652, Statute Book of Sweden). This sectoral responsibility, together with the rules in the Environmental Code, places a large responsibility on the SNRA. This requires that research and development efforts be focused on the most relevant relationships within the system of winter maintenance operations and their effects in order to avoid unpleasant surprises such as unforeseen claims for damages or judicial processes. Regarding the judicial aspect of the issue, the situation is still somewhat unclear in Sweden, since the issue has not yet been tried in the courtroom.

Environmental costs (Figure 1) also imply additional components to those described in this study. These include, for example, effects on groundwater, soil physics, and soil chemistry that not only lead to secondary impacts on vegetation but may also affect human health and the state of the natural and cultural environment. Long-term effects of the use of deicing salt on groundwater and surface waters are described by Thunqvist in a paper in these proceedings.

Tolerance Limits and Indicators

In today's winter operations in Sweden, the general recommendation is to "use as little salt as possible." It can be argued, however, that this recommendation is not based on an environmental concern as long as the two words "as possible" are connected only to requirements for a specific road surface friction value or snow depth tolerance limit. In fact the regulations specify no environmental tolerance limits.

On the other hand the salting strategy could also be interpreted to mean "use as much salt as possible." In this case the words "as possible" should be based on the long-term tolerance limits of human health and nature, a basic concept in the government bill on which the current transportation policy is based (Government Bill 1997/98:56, Transport Policy for Sustainable Development).

So far most studies on salt tolerance limits with regard to vegetation damage have been concerned with concentrations of sodium and chloride in plant tissue (*3, 15*). From the road administrator's point of view, however, this indicator is not very useful. A more important indicator would be the relation of deicing action (amount, method, technique, and timing) to the occurrence of damage, which would ultimately reveal what deicing strategy should be used on each individual occasion.

The extent of deicing damage has been classified in numerous investigations, but these have been devoted almost exclusively to only one impact—the stress compartment (Figure 9). In comparing different investigations of damage rates, it is evident there is a need for a uniform damage rating system, as many different damage rating systems make comparisons difficult. What is more important, however, is that adequate indicators be assigned to all impacts at all system levels (driving forces, pressures, states, and responses).

Robinson et al. (*8*) have stated that "A key challenge for the road manager is to find ways in which to describe the problems and impacts of road maintenance that can be understood by the politicians and the general public." It could be added that a crucial challenge for the scientific community is to find the key parameters and indicators for each of the system's different levels (driving forces, pressures, states, and responses) that can be understood and utilized by road managers. Monitoring the system on the proper spatial and temporal scales using adequate indicators will not only strengthen the scientific understanding of the system's ecological effects, but it will also increase the potential of taking appropriate measures that will improve the sustainability of the system.

Conclusion

Deicing salt usage and its effects on vegetation are complex; however, the new legal situation in Sweden requires the road authority to possess a proper understanding of this system.

A suitable model of the system is the DPSIR model, which takes into account the entire process from the societal need for transportation to actual impacts to required responses. To acquire the knowledge needed to take effective countermeasures against undesired impacts, the system must be monitored using adequate indicators at all its levels.

ACKNOWLEDGMENTS

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Long-Term Effects of Deicing Salt on the Roadside Environment
Part II: Groundwater and Surface Water

Eva-Lotta Thunqvist

Traffic can pose a serious pollutant threat to groundwater and surface water in its vicinity. In Sweden, about 300,000 tons of sodium chloride are used annually by the Swedish National Road Administration in deicing and snow removal operations. Similarly, local municipalities and private property owners also use road salt. In Sweden as well as in other countries where the use of deicing chemicals is common in winter, deicing's impact on groundwater has been observed in small private wells as well as in larger municipal supplies. For lakes in Sweden, deicing's impact has been observed as stratification and high chloride concentrations during spring. The extent of deicing's impact can be investigated under a set of specific criteria as well as a method to estimate the long-term effects of deicing salt. The calculated steady-state chloride concentration can be used to identify risk-prone areas for groundwater and surface water before damage has occurred. The resulting prediction can then be used in deciding what areas to protect and what measures to adopt. The DPSIR (Driving force, Pressure, State, Impact, Response) method can be a useful tool in describing how a winter road maintenance system works today; however, to more comprehensively prevent damage to the environment, a more active approach is necessary.

As shown in Figure 1, traffic can pose a serious pollutant threat to groundwater and surface water in its vicinity. Examples of pollutants are salt used for deicing and dustbinding; metals resulting from corrosion of vehicles and road surface and tire wear; hydrocarbons from road surface wear, tires, exhaust, and oils; and hazardous goods discharged as a result of accidents. Pollutants move from the road to the surrounding environment through runoff from the road, airborne spreading, and infiltration of water from the road surface into the road area soil (as from road construction) (Figure 1). Different interactions are involved in the movement of pollutants from roads. For example, particles can be both dry- and wet-transported, runoff into ditches can be direct runoff from road surfaces as well as airborne deposits, and snow can contain both wet and dry deposition and later become runoff into ditches or water infiltrated into soil. Pollutant measurement samples can be obtained from road deposits, runoff, dry and wet deposition, snow and soil, surface water, and groundwater. Collected samples are analyzed for common road-related substances such as chloride, base cations, nutrients, metals, hydrocarbons, and total solids.

About 300,000 tons of sodium chloride are used annually in Sweden by the Swedish National Road Administration for deicing and snow removal operations (*1*). Local municipalities and private property owners also use road salt. Another factor in winter road maintenance is drivers' use of tire studs, which improve friction but increase the wear and effects of grinding on winter roads. The annual amount of road wear for the 1993–1994 winter season in Sweden was estimated at 300,000 tons (*2*). Wet surface wear was reported at seven times that for a dry surface; hence the grinding effect may be further intensified by the use of deicing salt (*3*).

Major roads in Sweden are annually deiced with 10 to 20 tons of sodium chloride per kilometer. The effects

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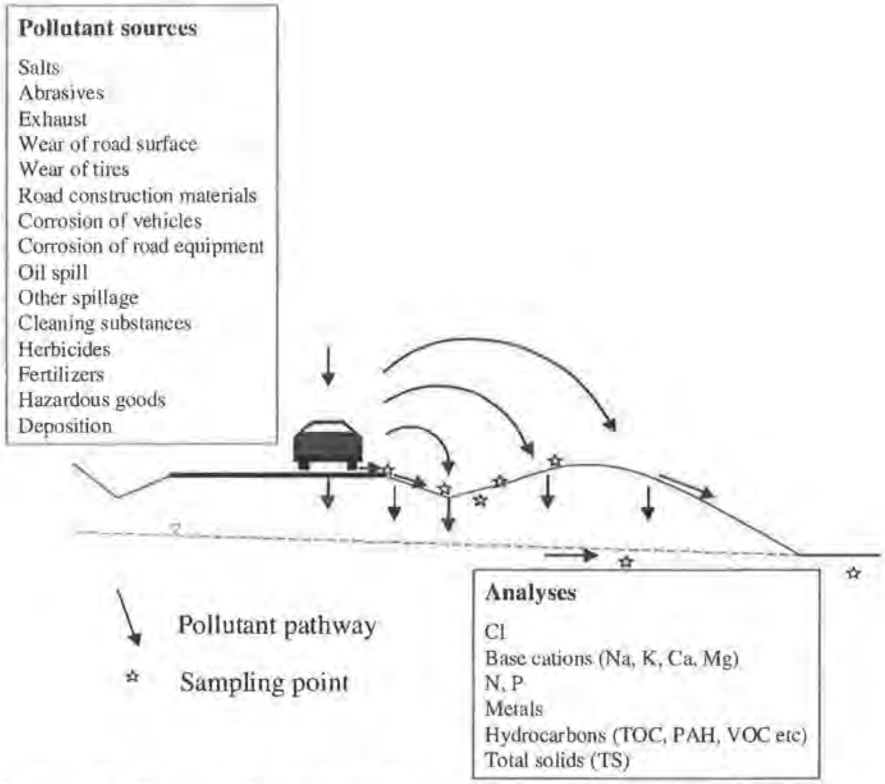

FIGURE 1 Conceptual model of pollutants from a road in operation, showing important sampling points and conceived pathways.

of salt are desired for the road, and in the ocean a high salt concentration is natural (Figure 2, Table 1). On their journey to the ocean, however, sodium chloride ions pass through an environment where the natural concentration of salt is low, thereby affecting the environment.

The chloride ion is a good tracer: it is conservative, highly soluble, and not subjected to retardation or degradation. A small part of the sodium may be retained in soil, but almost all the deicing salt will either infiltrate the soil or form runoff and will be found in groundwater and surface water. Other, nondegradable road-related substances may be retained in soil to a greater extent, but they too will eventually reach groundwater or surface water. Several investigations also show that heavy deicing salt application increases metal mobilization (*4–6*).

The aim of this study is to discuss the impacts of deicing salt applications on groundwater and surface waters.

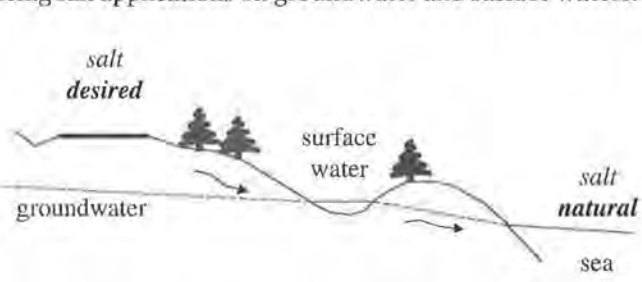

FIGURE 2 Movement of deicing salt from road to sea.

Toward that end the DPSIR (Driving force, Pressure, State, Impact, Response) method is used. It was determined that increased chloride concentrations are related to the natural concentrations of chloride.

Impact on Groundwater

In Canada and the United States, several studies show that groundwater close to major roads deiced with sodium chloride has increased chloride concentrations (*7–13*). The most important groundwater area in Finland, the Salpausselkä, is gradually becoming more salted because of deicing (*14*). In Norway and Denmark, chloride concentrations in groundwater close to major roads have also increased (*15, 16*).

For people on a sodium-restricted diet as a result of high blood pressure, congestive heart failure, or renal diseases, a high sodium level in drinking water implies health hazards. High chloride concentrations will increase the corrosion of pipes and vessels, thereby increasing metal concentrations in drinking water. Increased water hardness as a result of increased concentrations of calcium and magnesium ions due to ion exchange by sodium may also result in calcareous precipitation on utensils. High sodium concentrations in infiltrating water near roads will release

TABLE 1 Chloride Concentrations in Various Waters in Sweden (*1*)

Type of water	Chloride concentrations (mgl^{-1})
Rainwater	1 [1)]
Lakes	4 [2)]
Groundwater, dug wells	10 [3)]
Groundwater, drilled wells	15 [4)]
The Baltic Sea	3000 [5)]
Oceans	19000 [6)]

[1)] Median from 30 precipitation stations in Sweden 1996
[2)] Median from 5528 analyses of Swedish lakes 1983-1994
[3)] Median from 7645 dug Swedish wells
[4)] Median from 12455 drilled Swedish wells
[5)] Salt concentration 0.5%
[6)] Salt concentration 3.1%. Average seawater concentration of Cl in mM 545.0 .

heavy metals and lower the pH through ion exchange (*17*). They will also alter the soil structure, which may lead to an increased colloid-assisted transport of heavy metals (*6*). The formation of chloro-metal complexes may further facilitate heavy metal transport.

In areas where groundwater is discharged in the form of springs, enhanced sodium and chloride levels may affect the biota (*18*). The discharge of groundwater forms the base flow of streams, and high sodium chloride concentrations may affect surface water quality, as explained below. In addition, root uptake of salty groundwater may have an impact on vegetation (*19*).

In Sweden as well as in other countries where the use of deicing chemicals is common, deicing's impact on groundwater has been observed both in small private wells and in larger municipal supplies. The number of municipal groundwater supplies with enhanced chloride concentrations has increased in Sweden during the 1990s, and the number of municipal supplies with high chloride concentrations has also increased [Figure 3, in which the box in the legend ("Deicing salt") refers to the bar lines in the graph]. The impact is mostly seen in coarse soils, but there are also groundwater supplies in the bedrock that are contaminated by deicing salt. In a Swedish survey, environmental department directors in 115 out of 289 randomly selected communities were interviewed (*1*). In 7 percent of the communities, chloride concentrations in municipal supplies of more than

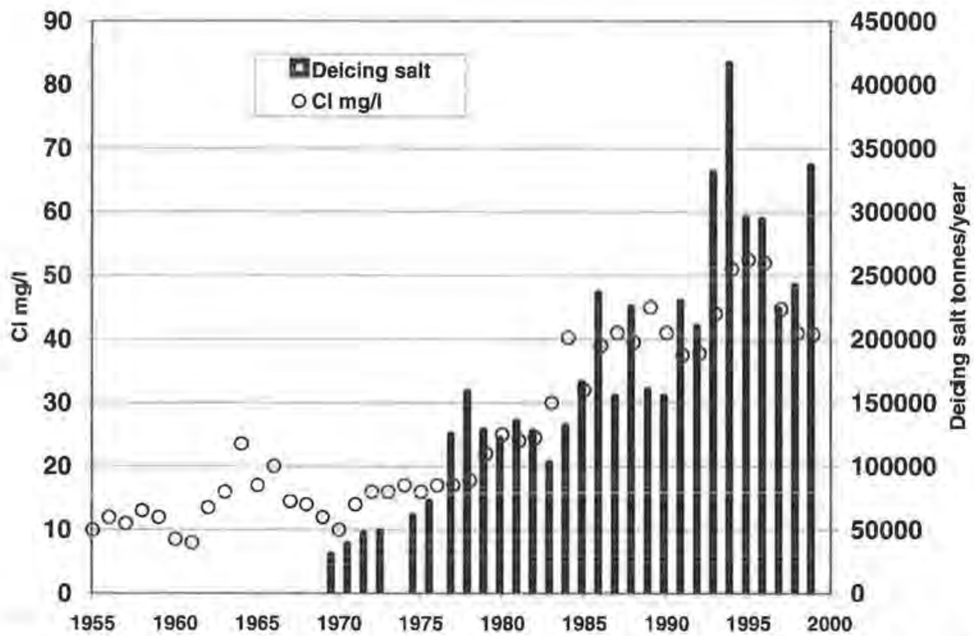

FIGURE 3 Median chloride concentration for 23 Swedish municipal water plants, 1954–1999, and annual application of deicing salt on national roads.

100 mg/L were reported. If the affected groundwater limit were established at 30 mg/L, an increased chloride concentration would be reported for 15 percent of the communities. There are of course other possible sources of chloride, including, for example, relict salt water, salt water intrusion, leakage from landfills, or sewage.

Some of the municipal supplies have been more thoroughly investigated (*20–23*). The increase in chloride concentration for 23 municipal groundwater plants during the period 1954–1999 is shown in Figure 3 together with the annual deicing salt application by the Swedish National Road Administration. The annual median value has been calculated for each plant, and the annual median chloride concentration of all plants is represented. Medians from the 1950s and 1960s are calculated for only a few plants since data from that period are sparse.

According to the Swedish National Road Administration, 41 cases of damage to private wells from deicing salt were reported in 1996 and 25 cases in 1997 (*1*). The extent of the salinized private well problem in Sweden has been investigated by Olofsson (*24*), Fabricius and Olofsson (*25*), Lindström (26) and Olofsson and Sandström (*27*). Contamination has been observed above the highest shoreline, where other sources are most likely eliminated (*27*).

Impact on Surface Water

Reports on the effects of deicing salts on surface water in Canada, the United States, and Norway show that elevated chloride levels in lakes can prolong the period of stratification and prevent the water from mixing completely during spring. This in turn may increase the volume of stagnant anaerobic bottom water (*28, 29*).

The impact of deicing salt may imply physical, chemical, or biological effects on surface water. Water with a high chloride concentration has a higher density; hence a chemocline can develop in a lake during winter and early spring resulting in denser, more salty water at the bottom of the lake. This stratification may affect the spring circulation and result in anaerobic bottom water, which in turn may affect the metal mobilization. Such changed conditions affect the biota and may lead to reduced diversity, shift in species and size of populations, or acute toxic effects. In small watercourses near roads, heavy applications of sodium may result in a lowered pH in the watercourse due to ion exchange (*30*).

Two Swedish lakes, Böksjön and Toren, were investigated from 1980 to 1982 (*31*). At the time of the study, the chloride concentration was enhanced, and during winter and early spring, stratification with higher concentrations was observed in the bottom water of both lakes.

Lake Böksjön is situated along the motorway E4, about 20 km northeast of the town of Norrköping. The motorway follows the western shore of the lake for about 500 m, and about 2.7 km of the road is drained to the lake (*1*). Concentrations of sodium and chloride increase every spring (Figure 4). Other lakes in Sweden used as municipal water supplies also have been reported to show increased chloride concentrations. These lakes include Bornsjön (the reserve water supply for Stockholm), Tjärnasjön in Borlänge, Älgviken in Nynäshamn, and Öresjö in Borås. In the case of Böksjön, the deicing of roads is the most likely reason for increased concentrations of chloride.

System Description by DPSIR

The Swedish Environmental Code (SFS 1998:808, ch.2) states that everyone is required to possess knowledge of the impact of one's activities and to implement protective measures to prevent their detrimental impact on human health or the environment. It is important to first understand a system to be able to appropriately respond with the correct measures. In Sweden, the Swedish Environmental Protection Agency uses the DPSIR model in its program for monitoring national environmental quality objectives (*32*). The model makes it possible to illustrate the Driving forces (D), Pressure (P), Impact (I) and Response (R) for a certain State (S). A generalized description of the model is given by Blomqvist in a paper in this proceedings.

In Figure 5, a box has been added to the original DPSIR model pointing out directives, laws, and policies that regulate the demand (D) and are the legal framework for the response (R). The response can include such actions as monitoring the state of groundwater and surface water or adapting adequate mitigation measures to

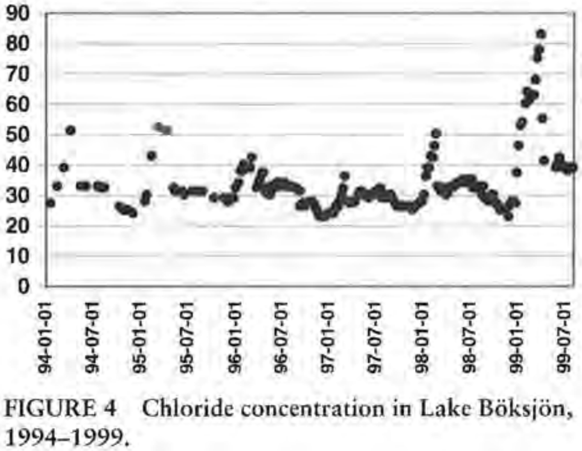

FIGURE 4 Chloride concentration in Lake Böksjön, 1994–1999.

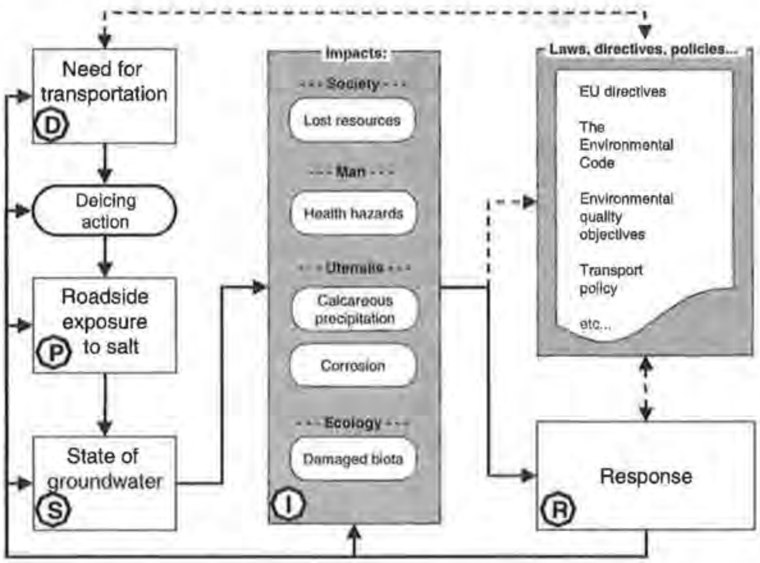

FIGURE 5 DPSIR model for the impact of deicing on groundwater.

prevent damage. Figure 5 also shows that deicing action is a consequence of the need for transportation, which in turn results in roadside exposure to salt.

In the case of groundwater, the driving force (D) is the need for transportation. The deicing action needed to facilitate transportation leads to the pressure (P), which is the roadside exposure to salt. The state (S) of groundwater depends on such factors as the amount of salt applied, the length of salted road within the catchment area, soil type, distance from road, size of the aquifer, and geology and hydrogeology in the area. Impacts (I) can be divided into several categories: loss of groundwater resources for society, health hazards to humans, effects on utensils, and impact on the environment. Estimating the value of the impact is a difficult task. However, there are methods for assessing the economic value of groundwater resources (*33*).

If the DPSIR model is used for illustrating the system of deicing and surface water, the state (S) will depend on such factors as the amount of salt applied, the amount of nonpermeable surfaces, the length of road within the catchment area, the topography, the road drainage system, and the turnover time for a lake. Impacts (I) on surface water can be also be divided into the categories of lost resources for society, health hazards for humans, and impacts on the environment (Figure 6).

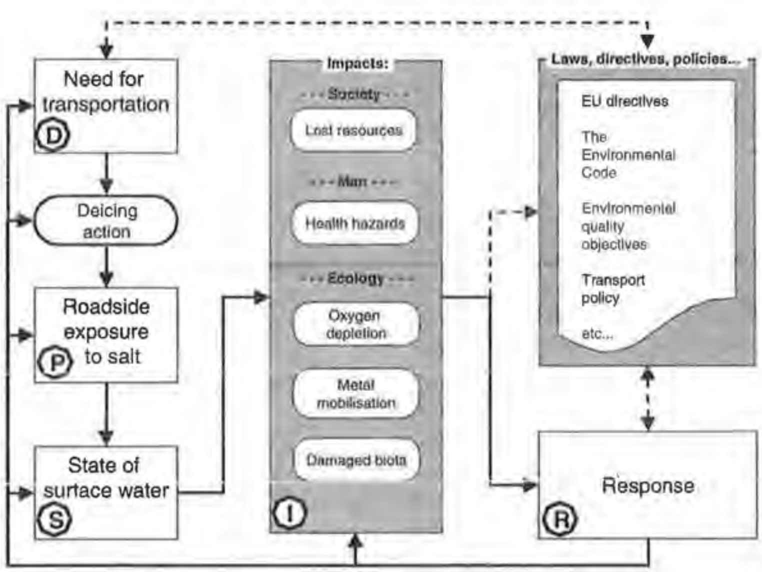

FIGURE 6 DPSIR model for the impact of deicing on surface water.

Criteria

Regulations in Sweden concerning the pollution of groundwater and surface water are formulated as national laws and policies and as directives from the European Union. These laws and directives are legal frames for discussing the question of sustainability and what nature can endure. Pollution of groundwater is generally a slow process because of the long turnover time for water. Once polluted, restoration of groundwater to natural conditions may take decades (*34*). Groundwater and lakes in Sweden generally show low background concentrations of chloride (Table 1). Chloride concentrations are higher in groundwater than in precipitation because of evapotranspiration (evaporation minus transpiration from vegetation); therefore higher concentrations of chloride exist in infiltrating and percolating water (Figure 7, in which the lines represent the different chloride concentrations, in mg/L, in infiltrating water).

The environmental quality criteria for groundwater, published by the Swedish Environmental Protection Agency (*35*), are shown in Table 2. The estimated values for chloride concentration in groundwater due to deposition are less than 20 mg/L in southern Sweden and 5 mg/L in the rest of the country.

FIGURE 7 Average chloride concentration (in mg/L) in infiltrating water, which forms recharge to groundwater (*35*).

TABLE 2 Environmental Quality Criteria for Chloride in Groundwater (*35*)

Class	Description	Cl	Effect
1	Low concentration	20	
2	Moderate concentration	20-50	
3	Relatively high concentration	50-100	
4	High concentration	100-300	Risk for corrosion of pipes
5	Very high concentration	>300	Risk for changes in taste

The Swedish National Food Administration recommends 100 mg/L Cl as a technical limit regarding corrosion, and 300 mg/L as an aesthetic limit for taste. There is no limit when the water is considered not suitable for consumption.

The environmental quality criteria for lakes and watercourses published by the Swedish Environmental Protection Agency (*36*) do not include chloride. There are, however, criteria for metals in water and sediment.

Steady State Concentration

The median values for chloride concentration in 23 municipal supplies (Figure 3) show an increasing trend. Compared to natural chloride concentrations due to background deposition, the increase is obvious. Although most pollutants eventually reach groundwater and surface water, it can be difficult to determine whether damage has occurred (for instance to a water supply). In some of the reported cases the chloride concentration has been extremely high on some occasions. Other water supplies also show an increasing trend for chloride concentrations. In Sweden, chloride analyses of water supplies are currently made once or twice a year, but it is often difficult to gather data for more than a few years back. Therefore actual trends are difficult to establish. Even if a water supply is sampled regularly (for example every March or April), other factors will influence the result, such as the weather during the preceding winter, the amounts of deicing salt applied that season, and aquifer discharge. Thus the actual measured chloride concentration in a storage is a function of the number of preceding seasons of deicing applications and the size of the storage.

Monitoring the state of groundwater or surface water by analyses of chloride concentration is in effect recording something that has already happened. It is

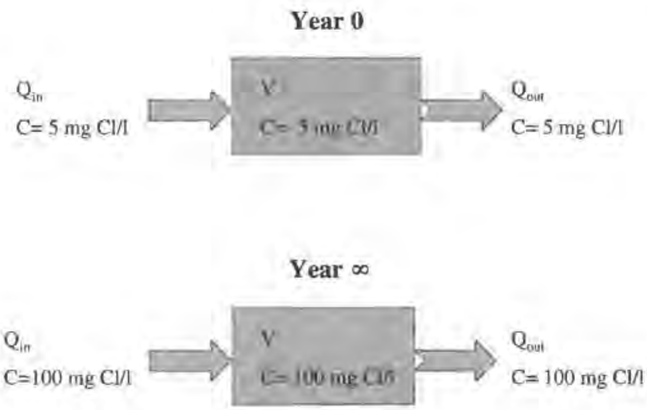

FIGURE 8 Complete-mix box model for increase in chloride concentration in storage.

therefore not always possible to know the extent of the impact of deicing salt. However, a prediction of steady state concentrations compared with natural concentrations can be used to identify the risk-prone areas for groundwater and surface water before the damage has occurred. In a simplified mass balance calculation, a complete-mix box model is assumed where outflow equals inflow and concentrations are the same from the beginning (equal to background concentration) for inflow, storage, and outflow (Figure 8).

During the first years of deicing salt application, chloride concentration in the recharge will be much higher than in the discharge. Hence chloride will accumulate in the storage and the concentration will increase. During conditions in which the salt application is invariable, the chloride concentration in discharge will eventually be the same as in recharge, thereby achieving steady state (which implies that the chloride concentration in the storage is the same as in infiltrating water). The increase in concentration as a function of time is an exponential curve (Figure 9).

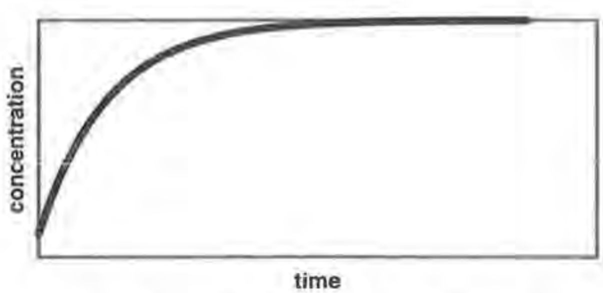

FIGURE 9 Exponential function for a complete-mix box model.

CONCLUSIONS

The interactions between different road related substances play a key role in this discussion. Investigations show that a large proportion of heavy metals is particle-bound. Emitted metals can therefore be transported on particles resulting from emissions and road wear and deposited in the vicinity of the road. The increased application of deicing salt may increase road surface wear by keeping the surface wet (*3*). In a study by Norrström and Jacks (*6*), it was shown that a large proportion of lead, zinc, and copper was present in chemical fractions susceptible to leaching when exposed to high sodium chloride concentrations. Heavy applications of deicing salt may therefore affect the mobility of other substances. Other combinative effects due to application of deicing salt are also possible.

Natural chloride concentrations in groundwater and surface water in Sweden are generally low. When given a certain criterion and method for estimating the increase in concentration, the extent of the impact can be investigated.

In this study the DPSIR method has been used to illustrate the current as well as traditional viewpoint that the need for transportation inevitably leads to roadside exposure to deicing salt. The DPSIR method can be a useful tool for understanding how we view the system today and for illustrating the environmental consequences of the use of deicing salt. However, there are also conflicting interests and different questions concerning priorities, and so from another point of view the demand could be such that the pollution of drinking water is not acceptable. This demand would lead to a pressure on transport policies.

Furthermore, the presumption that the need for transportation necessarily leads to roadside exposure to salt is questionable. An objection to the DPSIR method is that it is presently used in a passive way to monitor the consequences of deicing salt usage for groundwater and surface water. If the state (S) is related to specific criteria and a method for estimating long-term increases in concentrations, the DPSIR method would be a more powerful tool that could be used for more active measures.

There are even questions concerning how to assess deicing salt's impact. When given criteria as well as a method for estimating the long-term effects of deicing salt, however, the extent of its impact can be investigated. A simplified mass-balance method can be used to calculate steady state concentrations. The risk-prone areas for groundwater and surface water can then be identified, and decisions concerning what areas to protect and which measures to adapt can then be made.

The DPSIR method can be a useful tool for describing how the system of deicing salt application and its effects works today. To prevent damage to the environment, however, a more active approach is necessary.

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Decision Support Model for Assessing Net Public Benefits of Reuse of Waste Materials in Highway Maintenance and Construction Projects

William A. Hyman and Bruce L. Johnson

The state of Minnesota frequently receives requests from an outside source to consider accepting waste materials for reuse in highway maintenance and construction projects. The materials can include glass, roofing shingle tabs, shredded tires, coal ash, railroad ties, and taconite tailings. The Minnesota Department of Transportation (Mn/DOT) recently established a policy requiring that the use of waste material provide both short- and long-term public benefits. Mn/DOT also sought a framework to assess whether such benefits exist. Accordingly, a decision framework and decision support tool in the form of an electronic spreadsheet were developed, tested, and refined through the application of three case studies. The framework and decision support tool spreadsheet are described, and the results of one of the applied case studies are presented to illustrate the types of inputs required by the spreadsheet and the outputs produced. The spreadsheet is a very flexible tool that is able to account for a wide variety of materials and their placement in highways. It compares over a 20-year period the discounted present value of the incremental increase in highway maintenance and construction costs as a result of using taconite tailings in roads to the avoidable costs of disposal through transporting the waste and landfilling it or disposing of the waste material at the source where it is generated (e.g., a taconite mine).

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Frequently the Minnesota Department of Transportation (Mn/DOT) is asked to consider accepting waste products such as coal ash, shredded tires, roofing shingles, or mixed broken glass for use in highway maintenance or construction projects. The department recently established a policy delineating criteria under which it can accept waste materials from outside sources for use in highway maintenance and construction projects. The purpose of the policy is to ensure that Mn/DOT's decisions on waste materials and their recycling and reuse are made in a comprehensive manner respectful of environmental stewardship, public benefit, protection of public health, and limitation of liability.

Under the guidelines set out in the policy, Mn/DOT will accept waste from outside sources under the following criteria:

1. The waste must not be hazardous. Under no circumstances will Mn/DOT accept hazardous waste from others.
2. There must be both a short- and long-term public benefit from the reuse/recycling of waste materials.
3. The long-term effect of the reuse/recycling of waste materials must either improve the environment or, at a minimum, have a neutral effect on the environment.

The policy also states that, at a minimum, Mn/DOT must consider the following factors when assessing benefits and risks:

- Appropriate federal, state, and county agency approvals.

- Engineering performance of the structure incorporating the waste materials. (The performance must be equal to or better than that of the structure without the waste.)
- Constituents of the waste and the waste's toxicity.
- Environmental impacts from incorporating waste materials. (Environmental testing must show an impact equal to or less than that of materials currently used.)
- Recyclability of the new waste-amended construction material. (New material must have fewer or equal environmental impacts compared with nonamended material when recycled.)
- Short-term public benefit from reuse/recycling of waste materials.
- Long-term public benefit from reuse/recycling of waste materials.
- Legal and financial liability.
- Whether there are more cost-effective alternatives to disposing of wastes.
- Impact on Mn/DOT's mission of accepting non-Mn/DOT wastes.
- Potential use of pilot research and development experiments for further information.

Among the steps Mn/DOT recently took to render their policy operational was development of a framework and electronic spreadsheet for assessing two of the criteria listed above—the short-term as well as the long-term public benefit from the reuse/recycling of various types of waste materials—in deciding whether or not to accept waste material from outside sources. For this purpose Mn/DOT contracted with Booz · Allen & Hamilton, Inc. to develop a decision tree and accompanying spreadsheet. The project was carried out under the guidance and close cooperation of Mn/DOT staff.

This study describes the project's decision framework and electronic decision support tool, as well as application of the framework to one of three case studies used in testing and refining both the framework and spreadsheet.

FRAMEWORK

The decision framework focused on estimating the net economic benefit for reusing a particular waste material type. Net economic benefit was defined as the discounted present value of the difference between the future stream of avoidable costs for the normal disposal option and the future stream of costs for disposing of the waste material in highway maintenance or construction projects.

Figure 1 shows the decision framework, which is divided into five sections. The first two sections are used to determine whether the maximum annual quantity of waste can feasibly be used on a proposed portion of highway network. The maximum annual quantity is an analytic parameter for determining whether the roadway network has the capacity to absorb a proposed reuse of waste material. It is also used to explore whether there exist public benefits in the reuse of different quantities of a waste material type.

The remaining three framework sections describe steps for determining whether long- and short-term benefits exist in the use of waste materials in highway maintenance or construction projects.

Feasibility of Using the Maximum Annual Quantity

In the framework's first section, the decision maker first identifies how much of a particular type of waste will be disposed each year for 20 years, as well as the maximum annual quantity. A determination is then made concerning how many lane-miles, shoulder-miles, or embankment-miles will occur, as relevant, based on the following factors:

- Maximum annual quantity,
- An engineering specification for the quantity of waste per mile to be allocated for a particular use (i.e., pavement, base, subbase, shoulders, embankment), and
- Distribution of waste by functional class.

The framework's second section is an assessment of the annual levels of planned work and a determination of whether the maximum annual quantity of reuse will exceed the maximum feasible placement of waste for any functional class. If the maximum annual quantity exceeds the feasible placement for a particular functional class, it will then be necessary to reduce the maximum annual quantity, increase the specified quantity placed per mile, or change the distribution of placement of material across functional classes. If the maximum annual quantity does not exceed the feasible placement for a particular functional class, the decision maker can proceed to the next part of the decision framework.

Determination of Long- and Short-Term Public Benefits for Reusing a Waste Material

The remainder of the framework provides guidance on determining any long- and short-term benefits for reusing a waste material in highway maintenance or construction.

The third section is used to determine the discounted present value for each year during 20 years of the incremental change in the cost of the roadwork due to the proposed use of waste materials. Inputs for this calculation include the incremental change in delivered price of the material that would normally be used for incorporating the waste material, and other incremental changes in cost such as design, installation, inspection, and life-cycle costs such as maintenance and user costs.

The framework's fourth section is used to determine the avoidable cost of reusing waste materials in highways. The decision tree logic assumes that waste not reused or recycled in highways will either be disposed of at its source of origin or taken to a landfill. Depending on the disposal site and facility, avoidable cost will normally consist of several of the following items: tipping or cover fee, transport costs and facility capital, and maintenance and operating costs. These avoidable costs must be identified for each year during a 20-year period. The discounted present value is then calculated.

The decision tree's fifth section simply asks whether the discounted present value of the avoidable cost of disposing of waste materials in the disposal facility is greater than the discounted present value of the incremental costs of the proposed reuse of the waste for any short- and long-term periods over the next 20 years. If the answer is yes, there are net short- and long-term public benefits; if the answer is no, such benefits are nonexistent.

Electronic Spreadsheet Decision Support Tool

An electronic spreadsheet was developed in Microsoft Excel 97 to render the decision framework operational and to permit Mn/DOT to make calculations for determining whether short- and long-term benefits exist for reusing a waste material obtained from an outside source. The spreadsheet comprises a workbook of five sheets:

Sheet 1: Highway Inputs

This sheet is used to enter inputs for calculating the incremental costs of using a candidate waste material in the pavement, base, subbase, shoulder, or embankment of

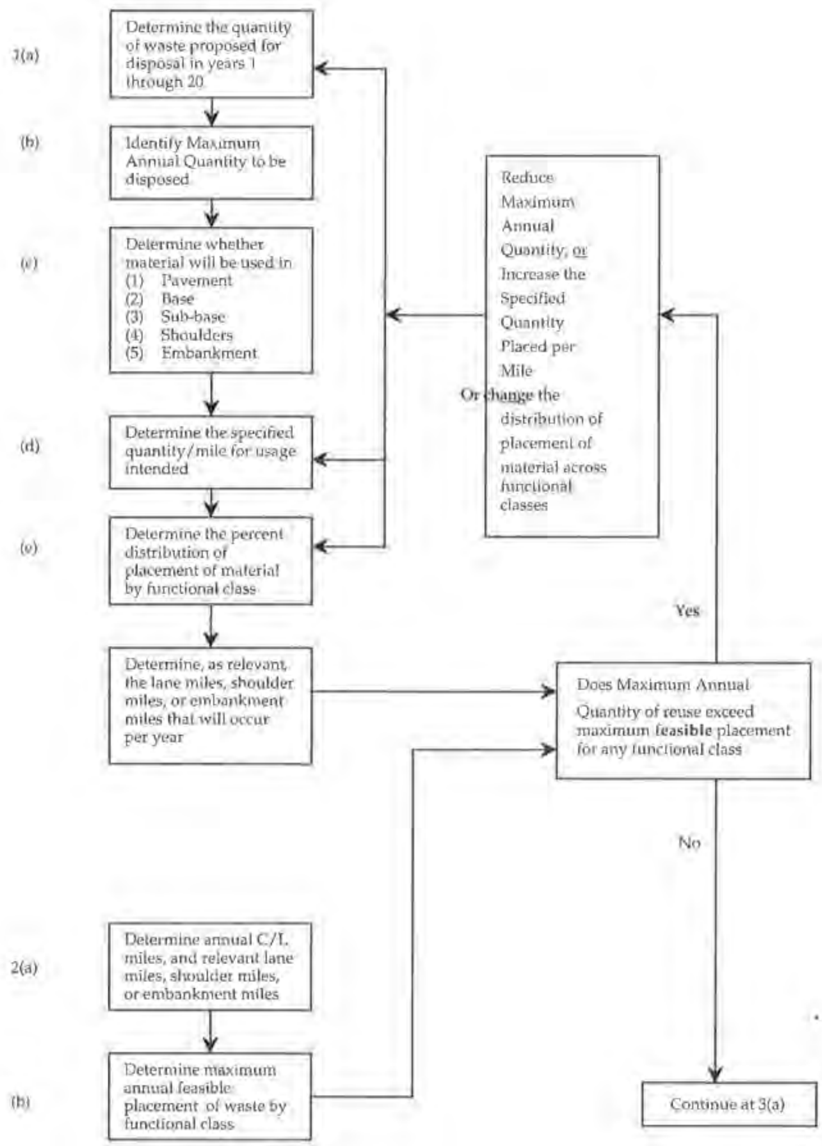

FIGURE 1 **Decision tree for determining public benefits of reuse of waste materials in highway maintenance and construction.** (*continued on next page*)

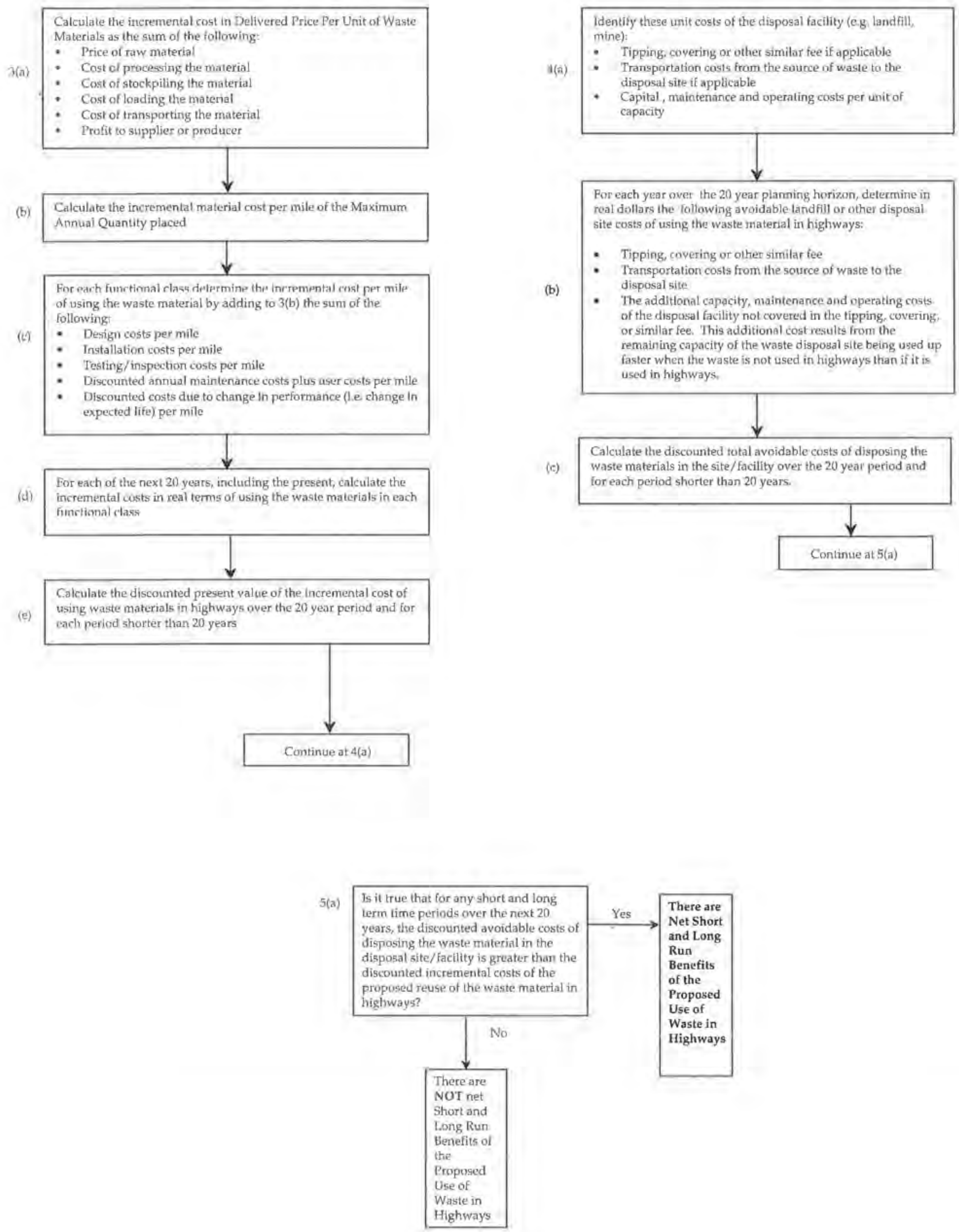

FIGURE 1 (*continued*) **Decision tree for determining public benefits of reuse of waste materials in highway maintenance and construction.**

highways and roads (Figure 2). The sheet performs calculations for determining the feasibility of placing the maximum annual quantity of proposed waste for use in roads given the planned annual centerline miles of relevant roadwork.

Required data inputs include the following:

- Maximum annual quantity of waste proposed for disposal;
- Fraction of maximum quantity to be disposed of each year for 20 years;
- Specified quantity of waste to be placed per mile in the proper units (i.e., lane-mile, shoulder-mile, embankment-mile);
- Location where waste is to be placed (e.g., pavement, base, subbase, shoulder, embankment);
- Distribution of waste by functional class;
- Ratio of various inventory features to centerline miles (e.g., ratio of lane-miles to centerline miles);
- Incremental cost of delivered price of waste material; and

SCENARIO FOR REUSE OF WASTE MATERIALS:		Normal Taconite Tailings Used in Highway Base -- Scenario B, Ship from Virginia MN to Taconite Harbor by Rail, Water & Hwy (04/13/99)			
Type of Material:	Norm. Taconite Tailings	DISCOUNT:	0.07	**(ENTER DISCOUNT RATE X 0.01**	
Use of Material:	Base				
MAXIMUM ANNUAL QUANTITY	126720	UNITS:	tons		
	MULTIPLIER	QUANTITY/YR			
Year 0	1.00	126720			
Year 1	1.00	126720			
Year 2	1.00	126720			
Year 3	1.00	126720			
Year 4	1.00	126720			
Year 5	1.00	126720			
Year 6	1.00	126720			
Year 7	1.00	126720			
Year 8	1.00	126720			
Year 9	1.00	126720			
Year 10	1.00	126720			
Year 11	1.00	126720			
Year 12	1.00	126720			
Year 13	1.00	126720			
Year 14	1.00	126720			
Year 15	1.00	126720			
Year 16	1.00	126720			
Year 17	1.00	126720			
Year 18	1.00	126720			
Year 19	1.00	126720			
TOTAL		2534400			
		Placement of Material (Enter 1 if placed there; 0 if not)			
Relevant coverage	Pavement	Base	Sub-base	Shoulders	Embankment
Units of coverage	Lane miles	Lane Miles	Lane miles	Shoulder miles	Embankment-miles
	01		0	0	0
SPECIFIED QUANTITIES PER MILE		Number of miles	Units		
Units placed per lane-mile	7634	16.59942363	lane-miles		
Units placed per shoulder mile		#DIV/0!	shoulder-miles		
Units placed per embankment-mile		#	embank.-miles		
	Freeways	Princ. Arterials	Min.Arterials	Collectors	Local
Lane-mi/centerline mile	0	2	2	2	2
Shoulder mi/centerline mile	0	2	2	2	2
Embankment miles/centerline mile	0	0.1	0.1	0.1	0.1
	Freeways	Princ. Arterials	Min.Arterials	Collectors	Local
Distribution of Placement (Total=1.00)	0	0.4	0.4	0.2	0

FIGURE 2 Inputs for determining feasibility of using waste materials and for assessing incremental highway costs. (*continued on next page*)

INCREMENTAL COST IN DELIVERED PRICE PER UNIT OF WASTE MATERIAL							
Price of Raw Material	-$0.27						
Cost of Processing the Material	-$0.46						
Cost of Stockpiling the Material	$0.00						
Cost of Loading the Material	$0.00						
Cost of Transporting the Material	$10.85	Note: Transport cost is calculated over the distance the waste is transported					
Profit to Supplier or Producer	$0.00						
TOT. DELIVERED PRICE/UNIT OF MTL.	$10.12	1282406.4 =MAX ANNUAL QUANTITY * TOT DEL PRICE					
MILES IN PROPER UNITS (Rows 34-36)	16.6						
MTL.COST/MI. OF MAX WASTE PLACED	$77,253	Note: This is in material cost per mile per year in the proper units (e.g. lane miles, shldr-miles, or emb.-mi) given the Maximum Annual Quantity.					
(miles expressed in proper units)							
	COMPONENT INCREMENTAL COSTS PER MILE IN PROPER UNITS BY FUNCTIONAL CLASS						
	Freeways	Prin.Arterials	Min. Arterials	Collectors	Locals		
Material Cost/Mi of Waste Placed	$77,253	$77,253	$77,253	$77,253	$77,253		
Design	$0	$0	$0	$0	$0		
Installation	$0	$0	$0	$0	$0		
Testing/Inspection	$0	$0	$0	$0	$0		
Discounted Annual Maintenance	$0	$0	$0	$0	$0		
Discounted Costs due to Chng in Perform.	$0	$0	$0	$0	$0		
TOTAL INC.COSTS.	$77,253	$77,253	$77,253	$77,253	$77,253		
	INCREMENTAL COST PER MILE MEASURED IN PROPER UNITS OF USING WASTE						
	In Pavements	In Base	In Sub-base	In Shoulders	In Embankments		
Freeways	$0.00	$77,253.40	$0.00	$0.00	$0.00		
Principal Arterials	$0.00	$77,253.40	$0.00	$0.00	$0.00		
Minor Arterials	$0.00	$77,253.40	$0.00	$0.00	$0.00		
Collectors	$0.00	$77,253.40	$0.00	$0.00	$0.00		
Local	$0.00	$77,253.40	$0.00	$0.00	$0.00		
	DISTRIBUTION OF WASTE GIVEN PROPOSED MAXIMUM ANNUAL QUANTITY TO BE DISPOSED						
	Planned Avg. C/L miles/yr		Planned lane miles	Lane-mi of waste	Planned shldr-miles	Shldr-miles of waste	Planned emb-miles
Freeways	0		0	0	0	#DIV/0!	0
Principal Arterials	4		8	6.639769452	8	#DIV/0!	0.4
Minor Arterials	4		8	6.639769452	8	#DIV/0!	0.4
Collectors	2		4	3.319884726	4	#DIV/0!	0.2
Local	0		0	0	0	#DIV/0!	0
Total	10		20	16.59942363	20	#DIV/0!	1

FIGURE 2 (*continued*) Inputs for determining feasibility of using waste materials and for assessing incremental highway costs.

• Incremental cost per mile of design, installation, inspection, and future maintenance costs.

Sheet 2: Highway Costs

This sheet shows the real and discounted incremental costs of using the waste material for each year over a 20-year planning horizon (Figure 3). Costs that are negative represent savings. No data inputs are required for this sheet.

Sheet 3: Take to Site (Landfill)

This sheet is used for entering data inputs to determine the avoidable costs for taking a candidate waste material from its source to a disposal facility, such as a landfill. Avoidable costs are calculated including (*a*) tipping, covering, or other such fee; (*b*) transportation costs; and (*c*) capital, maintenance, and operating costs not included (i.e., capitalized) in the tipping, covering, or other such fee. For capital, maintenance, and operating costs the sheet calculates the difference in costs for when waste is used in roads versus when waste is not used in roads.

Required data inputs include the following:

- Tipping or covering fee;
- Transportation costs;
- Capital, maintenance, and operating costs of the landfill per unit of capacity; and
- Additional capacity requirements.

For the key input of additional capacity requirements, the spreadsheet signals if the cumulative quantity of waste disposed of exceeds the remaining capacity for a particular year.

Sheet 4: Take from Site (Mine)

In some cases the source of a candidate waste material is the disposal site. For example taconite tailings proposed for use in highways would otherwise be disposed of at the source of the material—the settling basin of a taconite mine. Typically in such cases there is no tipping fee and also minimal or no transport costs. The main issue is the avoidable cost of capacity expansion. Using the waste material in highways delays the time for when expansion of the disposal facility is required, which results in avoidable costs (Figures 4*a* and 4*b*).

If the spreadsheet signals that the cumulative quantity of waste to be disposed of in a particular year exceeds the remaining capacity, the primary data input for this sheet is additional capacity required. The sheet also requires input data for capital, maintenance, and operating costs per unit of capacity.

Sheet 5: Net Benefits

This sheet adds the incremental costs of using the candidate waste in highways to the avoidable cost of not placing the waste in the disposal facility (Figure 5). Costs are calculated in real and discounted dollars for every year over a 20-year period. If the discounted costs of the sum of the incremental highway costs and the avoidable waste disposal costs are positive in the short and long term, then there are net public benefits over the short and long term.

Case Studies and Sample Spreadsheet Calculations

Three case studies were conducted during the course of this project to test the decision framework and spreadsheet and to refine them in an iterative manner. Each case study was realistic, based primarily on actual disposal facilities, but they included some hypothetical elements and inputs to simplify data collection. The three case studies were as follows:

- Case Study 1: Reuse of Taconite Tailings
- Case Study 2: Reuse of Mixed Broken Glass as Aggregate in Granular Base of Roads
- Case Study 3: Reuse of Roofing Shingle Tabs in Bituminous Pavement Mix

To illustrate the spreadsheet and its calculations, the remainder of this study describes in further detail Case Study 1.

Case Study 1: Taconite Tailing Reuse in West Iron Range, Minnesota

Problem Statement

Water quality in the Lake Superior watershed must be protected and preserved as directed by state and federal regulation as well as international agreements. The protection level assigned to the area is generally higher than for most other surface waters in Minnesota.

Acquiring aggregate along Lake Superior north of Duluth is becoming more difficult: the resource appears to be in adequate supply, but increasing complications are encountered when acquiring permissions to open new aggregate pits. The lack of aggregate sources appears most severe in Cook County (approximately 70 mi northeast of Duluth). However, from an engineering standpoint,

TOTAL COSTS OF USING WASTE											
*****IN PAVEMENTS*****	Freeways		Principal Arterials		Minor Arterials		Collectors		Local		YEAR TOTAL
YEAR	REAL	DISCOUNTED	REAL	DISCOUNTED	REAL	DISCOUNTED	REAL	DISCOUNTED	REAL	DISCOUNTED	REAL
0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
1	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
2	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
3	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
4	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
5	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
6	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
7	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
8	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
9	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
10	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
11	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
12	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
13	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
14	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
15	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
16	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
17	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
18	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
19	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
20 YEAR TOTALS	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
*****IN BASE*****	Freeways		Principal Arterials		Minor Arterials		Collectors		Local		YEAR TOTAL
YEAR	REAL	DISCOUNTED	REAL	DISCOUNTED	REAL	DISCOUNTED	REAL	DISCOUNTED	REAL	DISCOUNTED	REAL
0	$0	$0	$512,963	$512,963	$512,963	$512,963	$256,481	$256,481	$0	$0	$1,282,406
1	$0	$0	$512,963	$479,404	$512,963	$479,404	$256,481	$239,702	$0	$0	$1,282,406
2	$0	$0	$512,963	$448,041	$512,963	$448,041	$256,481	$224,021	$0	$0	$1,282,406
3	$0	$0	$512,963	$418,730	$512,963	$418,730	$256,481	$209,365	$0	$0	$1,282,406
4	$0	$0	$512,963	$391,337	$512,963	$391,337	$256,481	$195,668	$0	$0	$1,282,406
5	$0	$0	$512,963	$365,735	$512,963	$365,735	$256,481	$182,868	$0	$0	$1,282,406
6	$0	$0	$512,963	$341,809	$512,963	$341,809	$256,481	$170,904	$0	$0	$1,282,406
7	$0	$0	$512,963	$319,447	$512,963	$319,447	$256,481	$159,724	$0	$0	$1,282,406
8	$0	$0	$512,963	$298,549	$512,963	$298,549	$256,481	$149,274	$0	$0	$1,282,406
9	$0	$0	$512,963	$279,018	$512,963	$279,018	$256,481	$139,509	$0	$0	$1,282,406
10	$0	$0	$512,963	$260,764	$512,963	$260,764	$256,481	$130,382	$0	$0	$1,282,406
11	$0	$0	$512,963	$243,705	$512,963	$243,705	$256,481	$121,852	$0	$0	$1,282,406
12	$0	$0	$512,963	$227,762	$512,963	$227,762	$256,481	$113,881	$0	$0	$1,282,406
13	$0	$0	$512,963	$212,861	$512,963	$212,861	$256,481	$106,431	$0	$0	$1,282,406
14	$0	$0	$512,963	$198,936	$512,963	$198,936	$256,481	$99,468	$0	$0	$1,282,406
15	$0	$0	$512,963	$185,921	$512,963	$185,921	$256,481	$92,961	$0	$0	$1,282,406
16	$0	$0	$512,963	$173,758	$512,963	$173,758	$256,481	$86,879	$0	$0	$1,282,406
17	$0	$0	$512,963	$162,391	$512,963	$162,391	$256,481	$81,195	$0	$0	$1,282,406
18	$0	$0	$512,963	$151,767	$512,963	$151,767	$256,481	$75,884	$0	$0	$1,282,406
19	$0	$0	$512,963	$141,838	$512,963	$141,838	$256,481	$70,919	$0	$0	$1,282,406
20 YEAR TOTALS	$0	$0	$10,259,251	$5,814,736	$10,259,251	$5,814,736	$5,129,626	$2,907,368	$0	$0	$25,648,128

FIGURE 3 Real and discounted incremental highway costs over 20 years.

Year	Annual Qty Waste Disposed at Facility Less Qty Used in Hwys	Cumulative Amount Disposed	Begin Period Cumulative Capacity	Capacity Test: CUM.DISP>CUM.CAP?	CAPACITY ADDED	End Period Cumulative Capacity	Facility Costs with Reuse of Waste Materials in Highways			
							Capital Cost	Maint. Cost	Operating Cost	Total Cost
0	99873280	99873280	500000000	Capacity OK		500000000	$0	$1,000,000	$1,000,000	$2,000,000
1	99873280	199746560	500000000	Capacity OK		500000000	$0	$1,000,000	$1,000,000	$2,000,000
2	99873280	299619840	500000000	Capacity OK		500000000	$0	$1,000,000	$1,000,000	$2,000,000
3	99873280	399493120	500000000	Capacity OK		500000000	$0	$1,000,000	$1,000,000	$2,000,000
4	99873280	49936640	500000000	Capacity OK		500000000	$0	$1,000,000	$1,000,000	$2,000,000
5	99873280	0599239680	500000000	ADD CAPACITY	200000000	700000000	$8,000,000	$1,000,000	$1,000,000	$10,000,000
6	99873280	699112960	700000000	Capacity OK		700000000	$0	$1,400,000	$1,400,000	$2,800,000
7	99873280	798986240	700000000	ADD CAPACITY	1000000000	1700000000	$40,000,000	$1,400,000	$1,400,000	$42,800,000
8	99873280	898859520	1700000000	Capacity OK		1700000000	$0	$3,400,000	$3,400,000	$6,800,000
9	99873280	998732800	1700000000	Capacity OK		1700000000	$0	$3,400,000	$3,400,000	$6,800,000
10	99873280	1098606080	1700000000	Capacity OK		1700000000	$0	$3,400,000	$3,400,000	$6,800,000
11	99873280	1198479360	1700000000	Capacity OK		1700000000	$0	$3,400,000	$3,400,000	$6,800,000
12	99873280	1298352640	1700000000	Capacity OK		1700000000	$0	$3,400,000	$3,400,000	$6,800,000
13	99873280	1398225920	1700000000	Capacity OK		1700000000	$0	$3,400,000	$3,400,000	$6,800,000
14	99873280	1498099200	1700000000	Capacity OK		1700000000	$0	$3,400,000	$3,400,000	$6,800,000
15	99873280	1597972480	1700000000	Capacity OK		1700000000	$0	$3,400,000	$3,400,000	$6,800,000
16	99873280	1697845760	1700000000	Capacity OK		1700000000	$0	$3,400,000	$3,400,000	$6,800,000
17	99873280	1797719040	1700000000	ADD CAPACITY	400000000	2100000000	$16,000,000	$3,400,000	$3,400,000	$22,800,000
18	99873280	1897592320	2100000000	Capacity OK		2100000000	$0	$4,200,000	$4,200,000	$8,400,000
19	99873280	1997465600	2100000000	Capacity OK		2100000000	$0	$4,200,000	$4,200,000	$8,400,000
TOTALS							$64,000,000	$51,200,000	$51,200,000	$166,400,000

(a)

FIGURE 4 Waste material in highways: (*a*) avoidable costs with disposal. (*continued on next page*)

Year	Annual Quantity of Waste Processed At Disposal Facility	Cumulative Amount Disposed	Begin Period Cumulative Capacity	Capacity Test: CUM.DISP>CUM.CAP?	CAPACITY ADDED	End Period Cumulative Capacity	Facility Costs Without Reuse of Waste			
							Capital Cost	Maint. Cost	Operating Cost	Total Cost
0	100000000	100000000	500000000	Capacity OK		500000000	$0	$1,000,000	$1,000,000	$2,000,000
1	100000000	200000000	500000000	Capacity OK		500000000	$0	$1,000,000	$1,000,000	$2,000,000
2	100000000	300000000	500000000	Capacity OK		500000000	$0	$1,000,000	$1,000,000	$2,000,000
3	100000000	400000000	500000000	Capacity OK		500000000	$0	$1,000,000	$1,000,000	$2,000,000
4	100000000	500000000	500000000	Capacity OK		500000000	$0	$1,000,000	$1,000,000	$2,000,000
5	100000000	600000000	500000000	ADD CAPACITY	200000000	700000000	$8,000,000	$1,000,000	$1,000,000	$10,000,000
6	100000000	700000000	700000000	Capacity OK		700000000	$0	$1,400,000	$1,400,000	$2,800,000
7	100000000	800000000	700000000	ADD CAPACITY	1000000000	1700000000	$40,000,000	$1,400,000	$1,400,000	$42,800,000
8	100000000	900000000	1700000000	Capacity OK		1700000000	$0	$3,400,000	$3,400,000	$6,800,000
9	100000000	1000000000	1700000000	Capacity OK		1700000000	$0	$3,400,000	$3,400,000	$6,800,000
10	100000000	1100000000	1700000000	Capacity OK		1700000000	$0	$3,400,000	$3,400,000	$6,800,000
11	100000000	1200000000	1700000000	Capacity OK		1700000000	$0	$3,400,000	$3,400,000	$6,800,000
12	100000000	1300000000	1700000000	Capacity OK		1700000000	$0	$3,400,000	$3,400,000	$6,800,000
13	100000000	1400000000	1700000000	Capacity OK		1700000000	$0	$3,400,000	$3,400,000	$6,800,000
14	100000000	1500000000	1700000000	Capacity OK		1700000000	$0	$3,400,000	$3,400,000	$6,800,000
15	100000000	1600000000	1700000000	Capacity OK		1700000000	$0	$3,400,000	$3,400,000	$6,800,000
16	100000000	1700000000	1700000000	Capacity OK		1700000000	$0	$3,400,000	$3,400,000	$6,800,000
17	100000000	1800000000	1700000000	ADD CAPACITY	400000000	2100000000	$16,000,000	$3,400,000	$3,400,000	$22,800,000
18	100000000	1900000000	2100000000	Capacity OK		2100000000	$0	$4,200,000	$4,200,000	$8,400,000
19	100000000	2000000000	2100000000	Capacity OK		2100000000	$0	$4,200,000	$4,200,000	$8,400,000
TOTALS							$64,000,000	$51,200,000	$51,200,000	$166,400,000

(b)

FIGURE 4 (*continued*) Waste material in highways: (*b*) mining site costs without disposal.

Year	Discounted Costs without Reuse of Waste	Discounted Costs with Reuse of Waste	Discounted Avoided Costs
0	$2,000,000	$2,000,000	$0
1	$1,869,159	$1,869,159	$0
2	$1,746,877	$1,746,877	$0
3	$1,632,596	$1,632,596	$0
4	$1,525,790	$1,525,790	$0
5	$7,129,862	$7,129,862	$0
6	$1,865,758	$1,865,758	$0
7	$26,653,689	$26,653,689	$0
8	$3,957,662	$3,957,662	$0
9	$3,698,749	$3,698,749	$0
10	$3,456,775	$3,456,775	$0
11	$3,230,631	$3,230,631	$0
12	$3,019,281	$3,019,281	$0
13	$2,821,758	$2,821,758	$0
14	$2,637,157	$2,637,157	$0
15	$2,464,633	$2,464,633	$0
16	$2,303,395	$2,303,395	$0
17	$7,217,896	$7,217,896	$0
18	$2,485,257	$2,485,257	$0
19	$2,322,670	$2,322,670	$0
TOTALS	$84,039,597	$84,039,597	$0

FIGURE 5 Discounted avoided mining site costs of reusing waste in highways.

taconite tailing, a waste of iron ore mining, appears to be an acceptable replacement aggregate.

Taconite, which is a very hard rock that contains magnetic iron, has been open pit mined in northeast Minnesota since the 1950s. The rock is normally covered with till overburden, which is removed and stockpiled, thereby exposing the taconite. The taconite is drilled and blasted to a manageable size and then transported by truck or rail to a crusher. Water is added to the crushed rock, and the iron is extracted with electromagnets.

The remainder of the water and waste rock material is pumped to a large settling vat called a thickener, whose purpose is to separate water from the tailing. Flocculent chemicals are added to speed the settling process. The decanted thickener water is reused in the process, and the thickened tailing is pumped as a slurry from the bottom of the thickener tank to a type of monofill called a tailing basin.

The majority of tailing basins are enclosed by earthen dikes divided into subsections. Excess water in the basin is recovered for reuse. Tailing basins, which are permitted by the Minnesota Department of Natural Resources and the Minnesota Pollution Control Agency, are also designed to allow seepage water to discharge. Generally as one subsection of the basin fills another is opened for disposal.

The finished product from the mines is taconite pellets. The pellets are transported from each mine by rail to ship docks on Lake Superior. The pellets are then transported by ship to steel mills in Ohio and Illinois.

Some taconite mines import limestone from Michigan to enhance the quality of their pellet. For these mines, limestone is hauled back from the dock to the mine by rail.

Two of the six taconite mines have railroads leading to dock facilities on the northern parts of Lake Superior, in the towns of Silver Bay and Taconite Harbor (Lake and Cook counties, respectively). Unfortunately the tailing from both mines contains asbestos-like particles that are suspected carcinogens, and the U.S. Supreme Court has ordered the tailing be disposed of underwater and covered.

The four other mines lie west of the lake around the cities of Virginia and Hibbing. They all have railroad lines leading to dock facilities on Lake Superior, in Duluth Harbor. Among these mines, the closest tailing source to Cook County is approximately 130 highway miles away.

Assumptions and Calculations

Following is a partial list of assumptions and calculations for Case Study 1:

- Tailing available (all mines western range).
- Course tailing = 30 million tons/year.
- Normal tailing = 100 million tons/year.
- Price (Inland Steel, free on board, mine site—Virginia, Minnesota) = $0.50/ton.

- Truck (country driving) = 0.10/yd^3 to 0.15/yd^3 per mile.
- Truck (city or congested driving) = 0.15/yd^3 to 0.40/yd^3 per mile.
- Option for rail and barge (rail to Duluth estimated at 61 mi, barge/ship from Duluth to Schroder approx. 70 mi).
- Pit run aggregate = \$1.00/yd^3 to \$1.25/yd^3.
- Processed aggregate = \$2.00/yd^3.
- Density of aggregate = 15.5 ft^3/ton.
- Density of normal taconite tailings = 16.6 ft^3/ton.
- Assumed incremental processing cost = \$0.00.
- Normal taconite tailings would be used in base of reconstructed roads.
- Waste material used in base would be placed under the pavement surface only.
- All roads in Cook County in which waste material would be used are 2-lane with 12-ft lanes.
- Planned average reconstruction would be 10 mi per year distributed as 40 percent principal arterials, 40 percent minor arterials, and 20 percent collectors.
- Anticipated annual feasible placement of taconite tailings (126,720 tons of waste) is a tiny fraction of annual production of taconite tailings (100,000,000 tons per year), and this amount would have no noticeable effect on the timing of new taconite settling basin capacity expenditures.
- Reasonable assumed size of taconite settling basin is 12 to 13 mi^2.
- Capacity of some mines will be defined by the perimeter of the entire settling basin, whereas the capacity of other mines will be based on the capacity of the cell.
- Alternative assumptions for the size and timing of capital expenditures for settling basin capacity expansion as a test of whether maximum annual quantity of waste to be used in highways has any effect on the avoidable capital, maintenance, and operating costs of using the taconite tailings as base material in highways. (Under numerous alternative assumptions involving capacity additions of 200 million to 2 billion tons, given the relatively tiny amount of total available taconite tailings to be used in highways, the avoidable cost was zero.)
- Remaining capacity of the mines = 500,000,000 tons of tailings, implying 5 years of remaining life.
- Capital cost per unit of capacity = \$0.04 per ton; maintenance cost = \$0.002 per ton; and operating cost = \$0.002 per ton.

Alternative scenarios for transport and capacity expansion of taconite settling basin:

- Scenario A—Ship waste by highway from Virginia, Minnesota. Assumed a new settling basin with 2 billion

	TAKE WASTES TO DISPOSAL SITE (e.g. Landfill)				TAKE WASTES FROM DISPOSAL SITE (e.g. Mine)			
	DISCOUNTED PRESENT VALUE				DISCOUNTED PRESENT VALUE			
Year	Incremental Highway Costs	Avoided Costs of Not Using Disposal Site	Difference	Cumulative Savings (costs) through Year	Incremental Highway Costs	Avoided Costs of Not Using Disposal Site	Difference (Avoided -Hwy Costs)	Cumulative Savings (costs) through Year
0	$1,282,406				$1,282,406	0	-$1,282,406	-$1,282,406
1	$1,198,511				$1,198,511	0	-$1,198,511	-$2,480,917
2	$1,120,103				$1,120,103	0	-$1,120,103	-$3,601,020
3	$1,046,826				$1,046,826	0	-$1,046,826	$4,647,846
4	$978,342				$978,342	0	-$978,342	-$5,626,188
5	$914,338				$914,338	0	-$914,338	-$6,540,526
6	$854,522				$854,522	0	-$854,522	-$7,395,047
7	$798,618				$798,618	0	-$798,618	-$8,193,666
8	$746,372				$746,372	0	-$746,372	-$8,940,038
9	$697,544				$697,544	0	-$697,544	-$9,637,582
10	$651,910				$651,910	0	-$651,910	-$10,289,492
11	$609,262				$609,262	0	-$609,262	-$10,898,754
12	$569,404				$569,404	0	-$569,404	-$11,468,158
13	$532,153				$532,153	0	-$532,153	-$12,000,311
14	$497,339				$497,339	0	-$497,339	-$12,497,651
15	$464,803				$464,803	0	-$464,803	-$12,962,454
16	$434,395				$434,395	0	-$434,395	-$13,396,849
17	$405,977				$405,977	0	-$405,977	-$13,802,826
18	$379,418				$379,418	0	-$379,418	-$14,182,244
19	$354,596				$354,596	0	-$354,596	-$14,536,840
TOTALS	$14,536,840				$14,536,840	0	-$14,536,840	N.A.

FIGURE 6 Discounted net public benefits of reuse of waste.

TABLE 1 Results of Scenarios A and B

Scenario	Change in Highway Cost From Using Waste (Expressed in Discounted Present Dollars)	Avoidable Settling Basin Cost (Expressed in Discounted Present Dollars)	Avoidable Settling Basin Costs Less Change in Highway Cost	NET SHORT AND LONG TERM BENEFITS?
Scenario A. Transport wastes by highway and 2 billion ton expansion of settling basin upon exhaustion of remaining capacity	\$12.9 million	\$0	-\$12.9 million	NO
Scenario B. Transport waste by rail/barge/highway and expansion of settling basin in 200 million, 1 billion, and 400 million ton increments	\$14.5 million	\$0	-\$14.5 million	NO

tons of capacity, sufficient to dispose of 100 million tons for 20 years, would be constructed when remaining capacity was used up.

• Scenario B—Ship waste by rail 68 mi from Virginia, Minnesota, to Duluth, transfer to barge, transport 80 mi by water to Taconite Harbor in Cook County, transfer to truck and transport remaining distance by highway. Assumed transfer costs at \$0.10 tons/yd^3 and that additional settling basin capacity would be provided by settling basin cells with the following incremental capacities: 200,000,000 tons; 1,000,000,000 tons; and 400,000,000 tons.

Application of Decision Tree and Spreadsheet

The decision tree and spreadsheet were used to determine the yearly maximum feasible placement of taconite tailings in the base of highways in Cook County, Minnesota, and to assess whether net short- and long-term benefits existed for using the waste.

The decision tree's first page was used to determine whether the initial quantity proposed to be reused—100,000,000 tons of taconite tailings per year—was feasible given the maximum annual feasible placement of taconite tailings in the highway base by functional class. The answer was no. The proposed quantity of taconite tailings used annually was therefore reduced to 126,720 tons, a feasible level.

The remainder of the decision tree and spreadsheet were then applied under Scenarios A and B to determine whether the avoidable costs of using the taconite tailings exceeded the incremental change in the cost of using the taconite tailings in lieu of regular aggregate in the base. (Note that the example spreadsheets in Figures 2 to 6 refer to Scenario B only.) The results are presented in Table 1.

Conclusions

Reuse of waste materials in highway maintenance and construction projects is a critical area of public policy. Key issues include the effect of waste material on life-cycle costs, the ability to recycle parts of highways that contain waste materials, reduction of the waste stream produced by the economy at large, and the prevention of pollution. States need a framework and analytic tools for making decisions about whether net public benefits exist for using waste materials coming from sources outside a department. The experience of Mn/DOT in developing such a framework and corresponding decision support tool is testimony to the feasibility of quantitatively assessing the long- and short-term net economic benefits of using waste materials in highway maintenance and construction projects. Moreover, such a framework and decision support tool have an important role in practical decision making when states must decide whether or not to accept a waste material from an outside source.

Part 7

MAINTENANCE EQUIPMENT

Testing for FM Radio Interference in Motor Vehicles

Donald J. Lewis

The increased use of electronics in modern vehicles has led to compatibility problems between vehicle electronic systems and after-market electronic equipment typically installed in Texas Department of Transportation (TxDOT) vehicles. Radio frequency interference (RFI) between these electronic systems frequently produces random failure of both original equipment manufacturer and after-market components. Interference with TxDOT onboard two-way communication systems can significantly reduce the useful communication range. This interference problem must be analyzed and studied from the standpoint of the FM two-way radio's characteristics and the automotive systems. Other system interference problems can also occur. Failures of critical vehicle systems due to RFI can adversely affect the operation of these vehicles and pose grave safety problems. Guidelines for minimum acceptable RFI limits in motor vehicles must be examined and improved. The overall objective of this project is to develop and validate effective RFI test procedures that will allow TxDOT to identify potential compatibility and RFI problems related to the use of after-market equipment in its vehicles. The first step in this process will be to investigate RFI problems and current RFI test standards. After this review process, a detailed test procedure will be developed. The second phase of the project will be validation of the test procedure. The RFI test procedure to be developed will benefit not only TxDOT but other DOTs across the country as well.

The substantial and continual increase of microprocessor-based electronics in modern vehicles has led to compatibility problems between vehicle electronic systems and after-market electronic equipment typically installed in Texas Department of Transportation (TxDOT) vehicles. Radio frequency interference (RFI) between these electronic systems frequently produces random failure of both original equipment manufacturer (OEM) and after-market components. Interference with TxDOT onboard two-way communication systems can significantly reduce the useful communication range. Failures of critical vehicle systems such as engine control, antilock brakes, and air bags due to RFI can pose grave safety problems and adversely affect the operation of these vehicles.

RFI sources of particular concern include high-power, two-way mobile radios (multiple frequencies) and after-market alternative fuel conversion kits using microprocessor controllers. Although extensive RFI testing by vehicle manufacturers typically provides adequate protection for OEM-installed electronics, there is evidence of after-market equipment compatibility problems with two-way mobile radios, cellular phones, after-market alternative fuel conversion systems, and personal computers that merit both radiated and susceptibility RFI tests to include such equipment. Proper filtering of OEM systems appears to be insufficient with regard to compatibility with these common add-on systems.

There is a requirement to establish guidelines for minimum acceptable RFI limits in motor vehicles. Thus, the problem at hand is to develop and verify a test procedure that will identify potential RFI problems with both OEM systems and after-market systems and that is acceptable to both TxDOT and vehicle manufacturers.

It should be noted that TxDOT depends heavily on the reliable use of two-way radios (47 MHz) to conduct daily business. Reliable radio communication is critical

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to TxDOT's successful operation. The RFI test procedure to be developed will benefit not only TxDOT but other DOTs across the country as well.

Significance of Work

Radio frequency interference between electronic systems, although not a new problem, has become increasingly important. Modern aircraft are examples of systems with many complex electronic subsystems that must continue to work correctly in electrically noisy environments. A system with known components and a known layout can be tested for interference problems, and the problems can be corrected. However, if an additional electronic subsystem is added to the system later, there is no guarantee that the new system will not produce or receive interference.

This problem is particularly pronounced in new automobile systems. Modern cars can have multiple microprocessor-based systems that communicate with a variety of sensors and actuators throughout the vehicle. These are primarily digital systems operating at relatively high frequencies. The switching of the digital circuits generates even higher frequencies over a broad range of frequencies. Electromechanical systems, such as solenoids and electric motors, also generate electrical noise. Of course, the best-known noise source in an internal combustion engine is the ignition system.

Vehicle manufacturers go to great efforts to ensure that all the subsystems in a vehicle work correctly and are not affected by any electrical noise generated within the vehicle. To some extent, manufacturers also ensure that the vehicle works correctly in the presence of external interference signals. However, the manufacturer cannot test the vehicle under all conditions for after-market subsystems added to the vehicle. After-market items such as two-way mobile radios, cellular phones, alternative fuel conversion systems, and personal computers may cause problems with the existing vehicle electronic subsystems. In addition, the vehicle's subsystems may interfere with these added-on systems.

The SAE has been involved in writing electromagnetic compatibility standards since 1957. These standards are continually examined and updated to keep pace with technology. Comparable European standards also exist. Other organizations have developed standards for electromagnetic compatibility with many other systems. The U.S. military, the IEEE, and the American National Standards Institute (ANSI) all have a number of standards concerning electromagnetic compatibility.

The problem with developing a standard that takes after-market items into account has to do with the ways that electrical signals can be coupled between systems. For example, a two-way radio can produce or receive interference. The coupling can be through the antenna, the antenna cable, the power supply cables, other cables connected to the radio, or the radio's enclosure by direct radiation. Thus, the interference may be related not only to the radio and the vehicle but also to the way the radio is installed.

One approach to determining possible interference problems is to test the vehicle after the after-market items have been installed. Finding and fixing these problems, however, are time-consuming and expensive. In addition, they must be repeated every time there is a change or an addition to the vehicle's electronics. This is why standards are developed—to indicate to all parties (vehicle manufacturers, after-market vendors, and customers) what is required for their systems to work together without problems. The standards for electromagnetic compatibility must indicate not only acceptable limits but also how to measure the limits. This is crucial because of the wide variety of configurations that can exist.

It is also important that the add-on equipment, such as the FM two-way radio, be analyzed and studied to determine the processes by which it filters and/or preprocesses radio signals. This is essential in determining the cause and cure of interference problems.

Although the development of standards and standard test procedures sounds straightforward, it is very difficult because of the many ways interfering signals can be coupled. Standards must take all these possibilities into consideration. Historically, most of the disturbances in radio receivers in vehicles have been coupled through the antenna. However, this applies primarily to standard receivers in a fixed location in the vehicle and not as much to add-on two-way radios.

Radio frequency interference between these electronic subsystems can be a major problem. Interference with onboard two-way communication systems can significantly reduce the useful communication range. Interference may cause failure of critical vehicle systems that could adversely affect the operation of these vehicles and pose grave safety problems. New standards that address these issues are definitely needed.

Background

The recent avid use of microprocessor-based electronics in modern automotive applications has led to problems of compatibility between various pieces of after-market electronic equipment installed into the vehicular environment. As such, RFI between electronic systems has grown to such a magnitude that random failure of key automotive systems, both OEM and after-market, can affect the safety and operation of these vehicles.

Growing concerns of RFI failures involving anti-lock brake system and engine real-time management systems have become valid. Possible interference with air-bag deployment control systems is a concern. RFI sources that should be investigated include high-power, two-way mobile radios (multiple frequencies tested) and after-market alternative fuel conversion kits using microprocessor controllers.

Although extensive RFI testing by the OEM community apparently provides sufficient protection for OEM-installed electronics, there is evidence of after-market equipment compatibility problems (including two-way mobile radios, cellular phones, after-market alternative fuel conversion systems, and personal computers) that merit both radiated and susceptibility RFI tests to include such equipment. Proper filtering of OEM systems appears to be insufficient with regard to compatibility with add-on systems discussed above.

TxDOT continues to have problems associated with RFI in many aspects of its vehicular fleet. Although a test method was developed for detecting out-of-bound limits of high RFI levels in vehicles, RFI-related problems are not diminishing. Each new model year brings a new rash of problems, some the same, most unique. It is believed that the solutions (ultimately) will rely on the major vehicle manufacturers' adopting standards developed or initiated by TxDOT in order to be successful.

TxDOT has associated itself recently with SAE and its subcommittee on electromagnetic compatibility (EMC) charged with researching these issues. SAE currently does not have a test method for detecting the types of RFI considered important to the department. The closest test, SAE Test Method J551/4, -12, is inadequate for TxDOT needs and was recognized as such by SAE. SAE has reviewed the TxDOT test and believes it too is inadequate. Further development is necessary, according to SAE.

In addition, TxDOT recently received a call from the AASHTO subcommittee on communications requesting a copy of the TxDOT test. Efforts seem to be under way within AASHTO to consider the TxDOT test a recommended practice. This development reinforces the indications that there is widespread interest in a viable RFI test and that this research project should be pursued at this time.

Objectives of Research

The objectives of the proposed study are to

- Investigate the problems related to RFI between vehicle systems and TxDOT two-way radio systems,
- Analyze and study the processes by which the FM two-way radios filter and/or preprocess radio signals,
- Develop a detailed test procedure acceptable to both TxDOT and vehicle manufacturers that will identify potential RFI problems,
- Develop guidelines for after-market electronic equipment specifications and installation to minimize potential RFI problems,
- Verify the proposed test procedure via testing, and
- Formulate a numerical model for predicting RFI problems.

Implementation

The test procedure and equipment guidelines that result from this project can be implemented by TxDOT to minimize or eliminate RFI problems between OEM vehicle electronics and after-market electronic components such as two-way radios, cellular phones, alternative fuel engine control systems, and others. The results will be forwarded to vehicle manufacturers and to the SAE's Electromagnetic Radiation/Electromagnetic Interference Standards Committee for consideration in future vehicle design. The project results will also provide specific RFI levels for after-market equipment. The results will be provided to all state DOTs and other government-based vehicle fleets.

What TxDOT Has Done

It is believed that the current TxDOT signal plus noise and distortion (SINAD) test has established a good starting point. Further development and refinement are needed. Results from this project are being coordinated with proper officials within the SAE's EMC subcommittee for possible inclusion in future SAE standards or development of new standards. Only then will recurring RFI problems be eliminated by the incorporation of their solutions into the vehicle during development by the major vehicle manufacturers.

Research Initiated by TxDOT

The overall objective of this research project is to develop and validate effective RFI test procedures that will allow TxDOT to identify potential compatibility and RFI problems related to the use of after-market equipment in department vehicles. TxDOT recently contracted with Texas Tech University, which in turn had entered into subcontracts with both Allied-Signal, Inc., and Southwest Research Institute, for project implementation.

Principally, TxDOT plans to correlate test limits established with a department-developed 12-decibel SINAD test with those of SAE J551/4, -12 Test Standards. The department operates many two-way, 100-watt FM mobile radios in the 47-MHz range (and higher). A growing number of

RFI-related or -induced malfunctions are experienced every model year. For example, mobile radio receiver sensitivity has been greatly reduced in many high-noise-environment vehicles, while 100-watt mobile radio transmission often causes random and erratic effects on the vehicle electronic subsystems.

Ongoing Tasks

• Standards search. A detailed search was performed of various Federal Communications Commission, SAE, and other regulatory standards and specifications that relate to automotive RFI issues.

• Test plan development. A test plan was developed that will define what equipment to test, what frequency range to test, whether radiated and susceptibility emissions should both be tested, and what level of compatibility is acceptable. Recommended wording for inclusion in procurement specifications for vehicles and ancillary equipment will be developed along with instructions for proper installation of after-market equipment.

• Testing. Sample vehicles from the three major OEMs will be tested for RFI compatibility using representative samples of after-market add-on equipment. Limits established by the OEMs should be used as test standards initially. New limits should be established as tests determine weaknesses and vulnerabilities. Suggested RFI test formats to follow include military standards for RFI testing (Mil-Stds 461/462).

• Reporting. Reports will be generated that will give all project specifics including literature search criteria, type of tests needed, and development of an RFI test plan.

Potential Implementation

This evaluation will be continued through FY 2000 due to the growing awareness of safety as a real concern and issue. Results from tests should be forwarded to the major OEMs for consideration of incorporation into future vehicular designs and to state DOTs for incorporation into procurement specifications. Guidelines for "after-market" equipment suppliers should be generated defining specific levels of RFI limit compatibility requirements (both radiated and susceptibility) to be met.

Incorporation of the results of these tests by the major OEMs would result in widespread effectiveness available not only to the relatively limited user community listed above but also to the general traveling public.

Photometric Requirements for Arrow Panels and Portable Changeable Message Signs

Donald J. Lewis

Arrow panels and portable changeable message signs are often used in work zones to inform drivers of the need for a lane change or caution. The *Manual on Uniform Traffic Control Devices* (MUTCD) requires that Type C arrow panels have a minimum legibility distance of 1.6 km (1 mi). However, the MUTCD does not provide a subjective means for determining whether an arrow panel meets this criterion. Nor are there industry photometric standards for message panels. The purpose of this project is to develop a reliable and repeatable objective method for measuring the photometrics of arrow and message panels to ensure adequate performance. The research project tasks include a review of the state of the art, reviews of existing pertinent specifications, development of initial test methods, evaluations of arrow and message panel visibility and the effectiveness of the test methods, revisions and modifications of the test methods, and documentation of research activities and findings. The research findings will be described in a research report and a project summary report. The recommended test methods will be included in both documents.

Arrow panels (APs) and portable changeable message signs (PCMSs) are often used in work zones to communicate important information to road users. An AP is used to indicate the need for a lane change or caution on the part of the driver, whereas a PCMS is used to convey dynamic information that is not effectively communicated through static signing. Portable changeable message signs are sometimes referred to as message panels, and that term is sometimes used in this paper to denote a PCMS.

Although arrow and message panels have been used in traffic control applications for many years, there are no established photometric standards for either device that can be used as the basis for a procurement specification. For example, with arrow panels, the only provision related to visibility of these devices is a requirement in the *Texas Manual on Uniform Traffic Control Devices* (MUTCD)—*Part V1* W that indicates the minimum legibility of a Type C panel is 1.6 km (1 mi). There are no specifics that indicate how that legibility distance is measured. For message panels, the Texas MUTCD requires the sign to be visible at 0.8 km (½ mi) and the sign message to be visible at 200 m (650 ft). Again, there is no guidance on how these visibility requirements should be measured.

As a result of the lack of detailed measurement requirements, transportation agencies experience difficulty developing specifications that ensure that all arrow and message panels purchased by the agency will communicate the desired information to drivers in an effective and consistent manner. This research presents Texas Transportation Institute's (TTI's) plan for developing test methods for measuring the photometric properties of Type C arrow panels and portable changeable message signs. The intent of the test method is to provide the Texas Department of

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Transportation (TxDOT) with a measurable criterion for qualifying arrow and message panels for use on TxDOT projects.

Background and Significance of Work

Compared with most other types of traffic control devices, arrow and message panels are relatively new. Arrow panels were added to the national MUTCD in the late 1970s, and PCMSs were added in 1993. The body of research literature on arrow and message panels has primarily addressed the placement and effectiveness of the devices, with little research on their legibility and photometric properties. This can be attributed to the fact that, until recently, arrow and message panels used diesel-powered incandescent lamps, and the performance was sufficient. However, the introduction of solar-powered arrow and message panels, combined with the use of flip-disk and light-emitting diode (LED) technologies, has created concerns about the ability of these devices to meet the minimum legibility requirements.

MUTCD Principles for Arrow and Message Panels

The unique characteristics of work zones require a level of traffic control that is beyond that normally required for a typical roadway. Many work zones present conditions that drivers would not typically expect to encounter. To provide drivers with the information needed to safely maneuver through a work zone, traffic engineers in the United States have developed a series of traffic control standards and guides for work zones. These guidelines, which are part of the MUTCD, address the traffic control elements of work zones and the use of various traffic control devices in the work zones. These principles are known as Part VI of the MUTCD. At the national level, Part VI was revised in 1993 and published by FHWA as a stand-alone document. In Texas, the TxDOT version of Part VI establishes the practices for work-zone traffic control. As with the national version, TxDOT recently revised Part VI and published it as a stand-alone document. There are only minor differences between the national and Texas documents.

Arrow panels are unique to work zones. They present a flashing or sequential display that informs drivers of the need to change lanes or drive with caution. The current guidelines for the design and application of arrow panels are contained in Section 6F-3 of the Texas Part VI. There are three types of arrow panels: A, B, and C. The Type C arrow panel, which is the subject of this proposal, is intended for use in high-speed, high-volume work zones. It has a minimum size of 2438 by 1219 mm (96 by 48 in.), with a minimum of 15 elements, and has a "minimum legibility distance" of 1.6 km (1 mi). Each type of arrow panel is capable of displaying a single flashing arrow (left or right), sequential chevron (left or right), a flashing double arrow (left and right), and caution (bar or four-corner box). The national Part VI also defines a sequential arrow, but this display has been dropped from the Texas Part VI.

Portable changeable message signs are described in Section 6F-2 of the MUTCD. This section requires the PCMS to be visible at 0.8 km (½ mi) and the sign messages to be legible at 200 m (650 ft).

Arrow and Message Panel Technologies

The early arrow panels and many message panels were diesel-powered and used incandescent lamps. These devices could produce displays seen at great distances and wide angles. They also produced operational and maintenance difficulties, creating environmental nuisances with fuel spills, fumes, noise, and glare. The lamps used in these panels were typically automotive fog lamps, which could be purchased easily at an automobile parts store but had little quality control for lens color, intensity, or filament orientation.

With the development of solar technology in the last few years, solar-powered arrow and message panels have been introduced as alternative traffic control devices for work zones. These units were quiet and environmentally friendly, requiring no fueling and little maintenance compared with their diesel counterparts. However, as with most new technologies, performance and quality were spotty across the breadth of the early manufacturers. When they were required to meet the same MUTCD legibility requirements as the diesel-powered arrow panels, issues of lamp intensity and lamp angularity emerged. Lamps used in diesel-powered arrow panels are higher wattage than the lamps used in solar-powered arrow panels and therefore have a much greater luminous intensity. Furthermore, diesel-powered arrow lamps can typically maintain visibility with an angularity of more than ±20 degrees horizontal and ±5 degrees vertical, whereas solar lamps typically maintain visibility with an angularity of ±12 degrees horizontal. Newer generations of solar-powered arrow panels have increased lamp technology research to address these visibility concerns, which in turn produced higher levels of quality control in lamp design and engineering. LED lamps are one of the lamp innovations that have become common, particularly in PCMSs.

NCHRP Arrow Panel Research Project

Concerns over the visibility of the solar-powered arrow panels led to a recent research project on arrow panel visibility sponsored by NCHRP. Before the initiation of the NCHRP study, there had been very little research on the luminous intensity required to provide visibility of arrow panels. Commercially available arrow panels using different bulbs and power systems provide varied levels of visibility because there are no performance standards. This variation is most evident in solar-powered arrow panels, which offer operational advantages but may not provide visibility levels comparable with those of generator- or line-powered units. The project was needed to ensure that arrow panels provide adequate visibility and adhere to performance requirements based on the critical visibility factors, and because of a need for practical procedures that can quickly and easily evaluate in-service performance of arrow panels. NCHRP Project 5-14, Advance Warning Arrow Panel Visibility, was conducted to

- Identify and evaluate the factors affecting the detection and recognition of arrow panels,
- Develop performance requirements for arrow panels operating under various conditions, and
- Develop practical, reliable means for checking arrow panel visibility, as perceived by the motorist.

Research Activities

The research plan for this project was developed and conducted by the Last Resource, Inc. (LRI) of Bellefonte, Pennsylvania. The research activities took place over a period of 3 years and were funded at $275,000. (It is worth noting that LRI will be the subcontractor to TTI for the proposed TxDOT arrow panel research project.) The NCHRP research included the following research activities:

- Review existing literature and current practices to identify factors that affect arrow panel visibility, including light source, intensity, beam pattern, color, electrical power consumption, panel size, panel and light source orientation, ambient lighting levels, dimming capabilities, sun shading, and power characteristics.
- Identify current practices for utilization, placement, maintenance, and in-service evaluation of arrow panels by contacting public agencies, utility companies, construction and maintenance contractors, and other users.
- Prepare an experimental plan and conduct the evaluation of the factors affecting the visibility of arrow panels. The evaluations include laboratory experiments; laboratory and field tests, analytical studies, computer simulations, or other procedures that cover a practical range of field situations; driver characteristics; day, night, and transitional ambient lighting conditions; and other environmental situations.
- Based on the findings of previous tasks, develop technical requirements necessary to ensure adequate arrow panel visibility.
- Develop simple, straightforward procedures for use by maintenance and field personnel to assess the adequacy of in-service arrow panel visibility and to initiate simple corrective actions to improve visibility, if necessary. Because arrow boards must provide reliable, consistent operation under a variety of field conditions, including highly variable ambient light levels and different roadway geometry, the procedures must be sensitive to these conditions.
- Prepare a final report that includes the requirements and procedures developed as appendices.

An arrow panel mock-up was an important tool in the conduct of the static field evaluations of arrow panel visibility. The mock-up was used to determine the optimal and minimal photometric requirements for daytime legibility among younger and older drivers. It was built to the specifications of a typical Type C AP and was mounted on top of a van at the recommended MUTCD specification for height. A laptop computer controlled the flash rate and stimulus, and set intensity levels through a digital interface that varied the voltage by pulse width modulation. When equipped with GE 4412A diesel-type lamps, the mock-up panel is capable of producing lamp intensities of more than 2,000 candelas. The evaluation results indicated that the lamp intensity needed to accommodate virtually all drivers at a threshold level was in the range of 30 to 50 candelas.

In a follow-up dynamic evaluation, LRI evaluated performance as a function of arrow panel model with test subjects in a moving vehicle. The results indicate that the 100-candela arrow panels had a 95th-percentile identification distance of 473 m (1,552 ft), which is greater than the decision sight distance of 457 m (1,500 ft). In the dynamic evaluation, arrow panels with the 50-candela intensity established by the static evaluation had a 95th-percentile identification distance of 296 m (971 ft), a distance too low for high-speed roads but acceptable for low-speed roads.

Current Status

This project has been completed by LRI, and the report is currently under review by the NCHRP panel. Included in the report are procedures for

- Arrow panel photometric measurements,
- Maintenance personnel (to ensure proper visibility of arrow panels during repair), and
- Field personnel (to ensure visibility of arrow panels while in service).

The report is expected to be published by NCHRP in the near future.

Project Results

The results of the research have been summarized in one published paper. The research supports the use of 100 candelas as the minimum arrow panel intensity needed for daytime identification in high-speed situations and 380 candelas/lamp as the maximum allowed to control glare at night. The research suggests the intensity requirements shown in Table 1. These recommendations are based on the assumption that, for high-speed roads, the arrow panel message must be properly identified at 457 m (1,500 ft) at any viewing angle that meets appropriate geometric design standards. This distance provides a more-than-adequate decision sight distance for driver safety. With regard to angularity, accepted geometric standards indicate that arrow panels should be legible at ±8 degrees horizontal and ±3 degrees vertical on high-speed roads.

In summarizing the project findings, the researchers stated "that an arrow panel with lamps that meet the minimum intensity requirements within the suggested beam width requirements will not only better provide for motorist safety than the requirement for 1 mile legibility in the MUTCD, but also enable more cost-effective operation. The MUTCD requirement for 1 mile of legibility should be changed because it fails to guarantee visibility at any angle of viewing other than on-axis. 1 mile off-axis requirement is just not practical or necessary." The researchers also note that most, if not all, arrow panels that conform to the proposed requirements will also meet the current MUTCD 1-mi legibility requirement because the MUTCD does not specify observer age or viewing angle.

Arrow Panel Specification

The researchers considered two approaches for developing photometric specifications for arrow panels: in terms of either the entire panel or each individual lamp. Due to the ease of testing, the individual lamp approach was selected. The photometric requirements for arrow panels can be represented in terms of luminance (candelas per square meter) or in terms of luminous intensity (candelas). Luminous intensity was selected because at 300 m (984 ft) and beyond, the lamps on an arrow panel are clearly point light sources. The specification is based on the intensity and angularity requirements shown in Table 1. The required intensity levels in the specification were developed from the static and dynamic evaluations. However, the angularity requirements were developed from typical road geometries described in the AASHTO Green Book. The intention was to provide a structured framework for a department of transportation to develop its own angularity requirements based on typical road geometries found in the state.

Arrow Panel Photometric Measurement Procedures

One of the results of the NCHRP project is a potential procedure for measuring the photometric properties of arrow panels. An early version of the procedure is described in an appendix of the NCHRP report, and a more refined version of the procedure was presented at a recent Illuminating Engineering Society of North America conference and has been published in its publication. In essence, the procedure uses a luminance meter to measure the luminance and converts the measurement to an intensity value. The procedure can be used when the target source is small and does not fill the aperture of the luminance meter.

Unanswered Questions

As with most research projects, the NCHRP/LRI effort was not able to address all the issues associated with the visibility of arrow panels. A few of the unresolved issues that remain after completion of that study include the following:

- The legibility evaluations were conducted only in the daytime. The nighttime intensity levels were developed using the method for traffic signals, which is basically a 30 percent reduction from the daytime values. There is a need to evaluate legibility under actual nighttime conditions.
- The angularity requirements were developed from the geometric conditions that might reasonably be expected to occur in the field. The legibility evaluations did not include the effects of angularity on identification of the arrow panel message.
- The researchers focused attention on the use of intensity as the basis for the specification. Methods of specifying photometric performance for the entire panel were not developed.

NCHRP Project Implementation

Because the NCHRP project results have yet to be published, it is difficult to predict how the results will be implemented. Because the NCHRP research program is funded through AASHTO, it is expected that state transportation agencies will look closely at the results and consider adoption of the recommended arrow panel specification.

TABLE 1 Minimum Arrow Panel Luminous Intensity Requirements for High-Speed Roads

Situation and Angularity	Minimum (on-axis)	Minimum off-axis (➡8°horizontal, ➡3° vertical)	Maximum (within maximum angularity zone)
Daytime	500 candelas	100 candelas	none
Nighttime	150 candelas	30 candelas	380 candelas/lamp

In October 1998, NCHRP funded a small implementation effort ($15,000) to develop a procurement specification and application guideline for arrow panels from currently available information. This implementation effort, being conducted by TTI, is essentially a paper study to bring all available information together into a format that can be used by transportation agencies for procurement and application purposes.

Validity of Minimum Legibility Requirement

From the initial inclusion in the MUTCD, Type C arrow panels have had a requirement for a minimum legibility distance of 1.6 km (1 mi). Before the NCHRP project described previously, however, there was little research to support the use of this distance. A paper addressing the human factors considerations of arrow panels indicated that the optimal performance standard for high traffic density conditions should be that drivers identify the presence of flashing lights at 2.4 km (1.5 mi) and recognize the arrow symbol and direction at 1.6 km (1 mi). But that paper stated that "research does not describe arrow recognition distances. Our informal observations suggest that arrows are recognizable at approximately 1.6 km (1 mi) away, but further testing is recommended." It appears that the 1-mi legibility requirement was implemented because the arrow panels of that time (i.e., diesel-powered) were legible to most individuals at 1 mi. With the advent of solar power, the legibility requirement has become more difficult to meet, and manufacturers have begun to question the origin and validity of the 1-mi requirement for Type C arrow message panels.

As indicated by the NCHRP arrow panels research, the 1-mi minimum legibility distance requirement for Type C arrow panels is not justified. A more appropriate distance is 457 m (1,500 ft), which is consistent with the decision sight distance for high-speed roads in the original decision sight-distance research and the current AASHTO policy on geometric design.

As with arrow panels, there is little documented research that supports the 650-ft legibility requirement for PCMSs. Again, the requirement is probably based on an assessment of the best visibility distance that can be achieved with current technology.

Photometric Measurement of Arrow and Message Panels

As mentioned previously, the MUTCD requires that arrow and message panels meet a minimum legibility distance requirement. However, the MUTCD does not define the meaning of "minimum legibility distance." Nor does the MUTCD provide specifications for lamp sizes, lamp spacing, luminous intensity (candelas), or power supply. As a result, transportation agencies have difficulty enforcing this requirement when purchasing arrow and message panels. What is legible to one person at the required distance may not be legible to someone else (typically with poor eyesight). Or what is legible when viewed head-on may not be legible when viewed at an angle.

Providing a simple and consistent method of measuring the legibility of arrow and message panels is a complicated undertaking. It is especially complicated for the message panel. An arrow panel can be treated as a point light source, but a PCMS cannot. This makes it difficult to establish a photometric requirement for the overall unit. Some of the factors that complicate the legibility measurement include the following:

- Variations in observers, such as age, acuity, glare sensitivity, and contrast sensitivity;
- Variations in arrow and message panel technologies, such as incandescent lamps, LED lamps, flip-disk, diesel power, and solar power;
- Different displays (arrows, chevrons, and caution);
- The extended length of the legibility requirement;
- Restrictions imposed by the roadway geometry;
- Differences in performance characteristics between arrow panels and PCMSs; and
- Variations in the legibility characteristics of individual characters that can be used in a message panel.

Other complicating factors are the terminology and units associated with photometric measurements. Although the terms "luminance" and "illuminance" sound similar, for example, they have different photometric meanings. A term that is typically used by laypersons, such as "brightness," has no actual meaning. Figure 1 presents a few of the more basic terms used in photometric measurements. The use of metric units is another complicating factor. Photometric measurements have adopted metric units to a much wider extent than most other types of measurements.

Full-System Versus Multilevel Photometric Measurement

A number of methods can be used to measure the photometric quality of arrow and message panels. These methods can be divided into two types: full-system and multilevel. Both methods have advantages and disadvantages. Full-system measurements test the arrow and message panels as a complete system and may be the preferable method from a procurement perspective, but they are also the most difficult to achieve. Multilevel testing makes certain assumptions about how the arrow and

Brightness - The subjective attribute of light sensation by which a stimulus appears more or less intense or to emit more or less light.
Illuminance (E) - The amount of light falling upon an object. It is derived from luminous intensity by the "inverse square law" ($E=I/d^2$) where d is distance. It is expressed in foot candles (fc) or lux (lx).
Luminance (L) - A measure of light reflected from a surface or emitted by a light source, roughly equated to "brightness." It is not affected by distance and is derived from luminous intensity by dividing the luminous intensity by the source area. It is expressed in foot Lamberts (fl) or cd/m^2.
Luminous intensity (I) - A measure of the strength of a light source. It is expressed in candelas (cd).
Point light source - A light source whose detection is not affected by size, only luminous intensity.

FIGURE 1 Photometric terminology.

message panels will work as a system to reduce the test measurement difficulties.

When operating under real-world conditions, the arrow/message panel is functioning as a collection of several different subsystems. Each subsystem directly affects the performance of the panel as a whole. Because of these effects, the photometric quality is best tested when the arrow or message panel is functioning as a complete system. Under these conditions, the interaction of the power supply system and lamp system can be measured and monitored easily. The limitations to the types of measurements that can be made in a full-system test include the following:

1. Sensors cannot be used to measure the individual elements under full-system conditions unless the test setup blocks all extraneous light from the other elements from entering the measurement area of the sensor in question. Due to the close spacing of the elements, blocking extraneous light is very difficult. This means that the panels must be measured as a whole unit by a single sensor device. Accurate methods exist for completing such a test using various types of sensor devices. As with nearly all photometric measurement techniques of this type, a minimum separation distance is required between the sensor and the light source. Because the light source is an approximately 2.4-m (8-ft) wide panel, the separation distance is quite large, approaching at least 30.5 m (100 ft).

2. Assuming the above conditions are met, another limitation of a full-system test deals with the positioning of the panel under test. Arrow and message panels are large and heavy pieces of roadway construction equipment. There are two options for positioning the arrow or message panel for testing at various vertical and horizontal angles. The first is to move the arrow/message panel, but to do this accurately would require a specialized goniometer capable of moving the weight of the panel. Although this is not impossible, few if any independent photometric laboratories are equipped for such a task. Therefore, building specialized equipment would be required. The second approach is to move the sensor. It is much easier to move the sensor through the vertical and horizontal circular paths required to measure various angles. However, if the sensor is placed at 30.5 m (100 ft), an 11-m (36-ft) ceiling would be required in order to measure ±10 degrees vertical. The same is true for horizontal angles. If the laboratory is capable of such dimensions, then accurate full-system measurements are possible.

An alternative to full-system testing is to test the subsystems separately for certain test conditions and to test the complete system only under limited conditions. The main benefit of this approach is that certain tests that are difficult in full-system testing can be easily completed as subsystem tests. Then the required amount of full-system testing can be limited to monitoring the interaction of subsystems under a very limited and easily handled set of conditions. Such a hybrid method of testing could involve the following:

1. The photometric quality of the arrow and message panel lamp system would be measured using multilevel tests on a small number of actual lamps that are used in the panel. These lamps would be tested by independent photometric laboratories using standard testing procedures and standard goniometer equipment. Standard practices already exist for photometric testing of sealed-beam and other types of lamps commonly used in arrow panels. The resultant data would be used to determine whether the lamp under test meets the photometric requirements over the specified vertical and horizontal angular range. If the sample of lamps does not meet the photometric requirements, the arrow/message panel would fail the specification because placing the lamps in the actual arrow/message panel would not increase their effectiveness.

2. After a sample of lamps has passed the multilevel tests, simplified full-system testing would begin. This endurance-type test would monitor the interaction of the

power supply and lamp systems. However, because angularity was previously measured, light output would be monitored only at a single angular coordinate, preferably [0°, 0°]. Monitoring would be completed with an integrating sensor device, such as that developed for traffic signals. Such a device can be placed directly over the hood of an arrow panel lamp. This device can measure only at a single angular coordinate, but this limitation is not a problem for this type of test. After testing commenced, the light output at [0°, 0°] would be monitored until it fell below the required minimum level. Integrating devices can be placed on more than one lamp, if more lamp data are desired. For a message panel, only one element of the matrix would be illuminated for measurement.

The hybrid test method does have some drawbacks. The first is the assumption that the lamps used in the lamp system will all have nearly the same performance characteristics. Another is that the integrating sensor would have to be built for this application. These drawbacks are minor when compared with the simplification in testing. The lamp assumption is not unreasonable for two reasons: (*a*) lamp quality control achieved by solar panel manufacturers is very high, and therefore lamp-to-lamp uniformity is very good; and (*b*) multilevel photometry is standard practice in the automotive industry, where vehicle light sources, including headlamps, are tested at multilevel and not as a full system.

PROJECT IMPLEMENTATION

The sole purpose of this project is to provide implementable test methods that TxDOT can use in the procurement process for arrow and message panels. Providing the test method will help TxDOT ensure that arrow and message panels used on its projects will meet the performance criteria contained in the MUTCD and meet the needs of drivers approaching a work zone.

WORK PLAN

Any research project must have a clearly defined goal that provides an overall focus to the research activities. All activities must contribute to the realization of the research goal. Progress toward meeting the goal is measured through quantifiable objectives, which are used to determine the necessary research activities. With this in mind, the following goal has been established for this research project:

> Develop photometric test methods that will provide objective means of ensuring that arrow panels and portable changeable message signs used on TxDOT projects meet the visibility needs of drivers.

Using this goal, the following specific and quantifiable objectives have been established for this research project:

- Maintain continuing and effective communication with the TxDOT project director and project advisors.
- Identify relevant findings from previous evaluations of arrow panels and portable changeable message signs.
- Identify relevant arrow and message panel practices in other state transportation agencies.
- Synthesize pertinent information from the NCHRP arrow panel research project.
- Identify previous research on the legibility of arrow and message panels, and determine an appropriate legibility distance to be used as the basis for a test method.
- Develop arrow and message panel photometric test methods for evaluation.
- Evaluate the visibility of various arrow and message panels in field experiments, and determine an appropriate minimum legibility requirement for the test methods.
- Evaluate the relative performance of full-system and multilevel photometric test methods and the ability of commercial laboratories to implement each method.
- Develop a reliable, repeatable, and defensible arrow and message panel photometric test method that can be performed at a reasonable cost.
- Document the activities and findings of the research project.

The objectives of this research project will be met through the conduct and completion of a carefully formulated work plan. This work plan has been structured to provide TxDOT with a useful, practical, and reliable method for testing arrow and message panel photometrics.

The project will consist of two phases. In the first phase, researchers will develop the photometric requirements for arrow panels. This work will take place during the first year of the project. The second phase will address the photometric requirements for portable changeable message signs and will take place primarily during the second year. However, some work on this phase will occur during the first year when there is overlap with the arrow panel effort. Research continues. The project is scheduled to be completed in August 2001.

Implementing Next-Generation Maintenance Vehicle Technology

Leland D. Smithson

Transportation agencies are facing ever-increasing demands from the customers they serve for safer, faster, and more reliable transportation systems. This is especially true for highway transportation because nearly all trips begin and end using the roadway. To add to the challenge, most public agencies are being asked to downsize, improve efficiency and effectiveness, and provide real-time status of the roadway system so that the motoring public can make better travel plans and decisions. The progress is described that three Midwest states are making on improving the efficiency and effectiveness of snow and ice control operations with improved equipment, road/weather forecasting, and interfacing with the National Intelligent Transportation System Architecture for improved customer communication.

The mission of the Iowa Department of Transportation's Maintenance Division is to manage the preservation and operation of Iowa's transportation system to deliver transportation services that support the economic, environmental, and social needs of its customers. This mission is particularly challenging to Snow Belt states during the perils of a winter season. Just-in-time goods deliveries, a key ingredient in any state's economic vitality, place an ever-increasing importance on reliable year-round transportation. These increasing transportation demands are coming at a time when most states are being asked to downsize their maintenance operations work force. The application of advanced snow and ice control technologies and their integration with intelligent transportation systems (ITS) offer excellent potential for increasing operational efficiency and effectiveness as well as improving winter mobility and driver safety. In 1995, the state departments of transportation (DOTs) of Iowa, Michigan, and Minnesota formed a consortium to define and develop the next-generation highway maintenance vehicle that would use the latest maintenance operational technologies and interface with ITS. Focus groups consisting of each DOT's internal and external customers revealed that, although all maintenance operations could benefit from creating this new-generation vehicle, ice and snow operations were the most complex and would benefit greatly from improvements in state-of-the-art vehicle navigation systems, onboard computer applications, and enhanced safety systems. This advanced-technology highway maintenance vehicle functions as both an operational truck and a mobile data-gathering platform. Sensors mounted on the vehicle record air and roadway surface temperature, roadway surface condition, and roadway surface friction characteristics. This information is Global Positioning System–correlated and is used in maintenance operational decision making. The information eventually will be interfaced with the ITS technology in the Traffic Management and Information Service Provider Centers Subsystems of the National ITS Architecture.

The advanced-technology highway maintenance vehicle performs an important role in the FHWA's Weather Information for Surface Transportation ITS Field Operational Test being conducted by the Foretell Consortium.

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The vehicle operates as a mobile environmental sensor station gathering real-time pavement thermal profiles and air-temperature data for input to the Foretell microscale models.

Each consortium state has built and operated an advanced-technology highway maintenance vehicle in its daily maintenance operations for 3 years. Each vehicle and its advanced concept technologies have passed proof-of-concept tests. Each technology is now being evaluated to determine what benefits have been realized and to calculate their respective benefit/cost ratio. Emerging technologies are also being tested on the concept vehicle. First-generation concept technologies are being redesigned to improve their reliability and reduce complexity and cost. For example, a roadway friction-measuring device has been redesigned to make it smaller, less complex, and more durable, and the cost has been reduced by 65 percent. Reduced cost is especially important because each state will need several hundred friction-measuring units to adequately meet the need that rural ITS must accurately determine and predict the winter condition of road surfaces and its impact on braking and driving traction.

In recognition of the potential for using advanced methods and ITS technologies for highway maintenance activities, a four-phase study, shown in Figure 1, was initiated to define the desired vehicle and equipment capabilities for the next-generation highway vehicle, develop and evaluate prototype vehicles, conduct benefit/cost analysis, and produce maintenance vehicles for fleet applications. The initial focus is on maintenance operations that are most visible to the public. Transportation agency operations and ITS surveys have shown that safety and winter mobility rank high in customers' concerns and expectations. Winter snow and ice control operations, therefore, are receiving first consideration for technology applications in developing the next-generation highway maintenance vehicle.

Four-Phase Research in Process

Phase I

The objective of Phase I was to develop the functionality that the concept vehicle will provide and to enlist private-sector partners to provide the functionality. This phase began with a literature review of materials related to winter highway maintenance activities. One hundred five articles were collected that pertained to state-of-the-art equipment, technologies, and research related to winter highway maintenance activities.

The ideal capabilities of a winter maintenance vehicle were identified through focus groups. Five focus groups were formed. They included representation from equipment operators and managers, mechanics, resident and central maintenance office engineers, area supervisors, law enforcement, and emergency responders. Focus group meetings were held in the three consortium states generating more than 600 ideas. These were later combined and organized into a list of 181 desired capabilities for the highway maintenance concept vehicle. The final prototype design for the three prototype vehicles provided the following desired capabilities identified by the focus groups:

- Sense roadway surface temperatures,
- Sense roadway surface friction conditions,
- Record and download vehicle activities,
- Improve fuel economy,
- Provide adequate horsepower for the vehicle,
- Carry and distribute multiple types of materials,
- Provide removable salt/salt brine dispensing system, and
- Provide backup sensors/monitors.

Private-sector equipment and technology providers were introduced to the study and asked to join the effort. These private partners committed to providing equipment and expertise for the study's duration. Phase I is complete, and a more detailed discussion can be found in *Concept Highway Maintenance Vehicle, Final Report Phase I*, dated April 1997, Iowa State University, Ames, Iowa. The report is also on the Iowa State University Center for Transportation Research and Education (CTRE) website at http://www.ctre.iastate.edu/Research/conceptv/index.htm.

Phase II

The objectives of Phase II were to build three prototype concept vehicles, integrating the subsystems into a working system; conduct proof of concept; and prepare for field evaluations of three prototype vehicles in Phase III. Proof of concept was conducted for each of the functional areas integrated into the prototype vehicles. Proof of concept for Phase II was defined as conducting "end-to-end" processing, observing the success of the "end-to-end" processing, and observing if the data were reasonable. Proof of concept is not a rigorous, statistically valid field test. A data collection and observation plan was developed to conduct proof of concept while operating the prototype vehicles during the winter of 1998–1999.

In addition, telephone interviews were conducted with the prototype vehicle operators to ascertain equipment performance. The interviews and documentation of equipment performance led to guidelines for the desired equip-

Foundation Statements:

1. "The solutions must be selected and recommended based on a benefit/cost analysis and a reasonably short time to implementation."
2 " The application of solutions must be described in terms that related to improving *service to customers*."

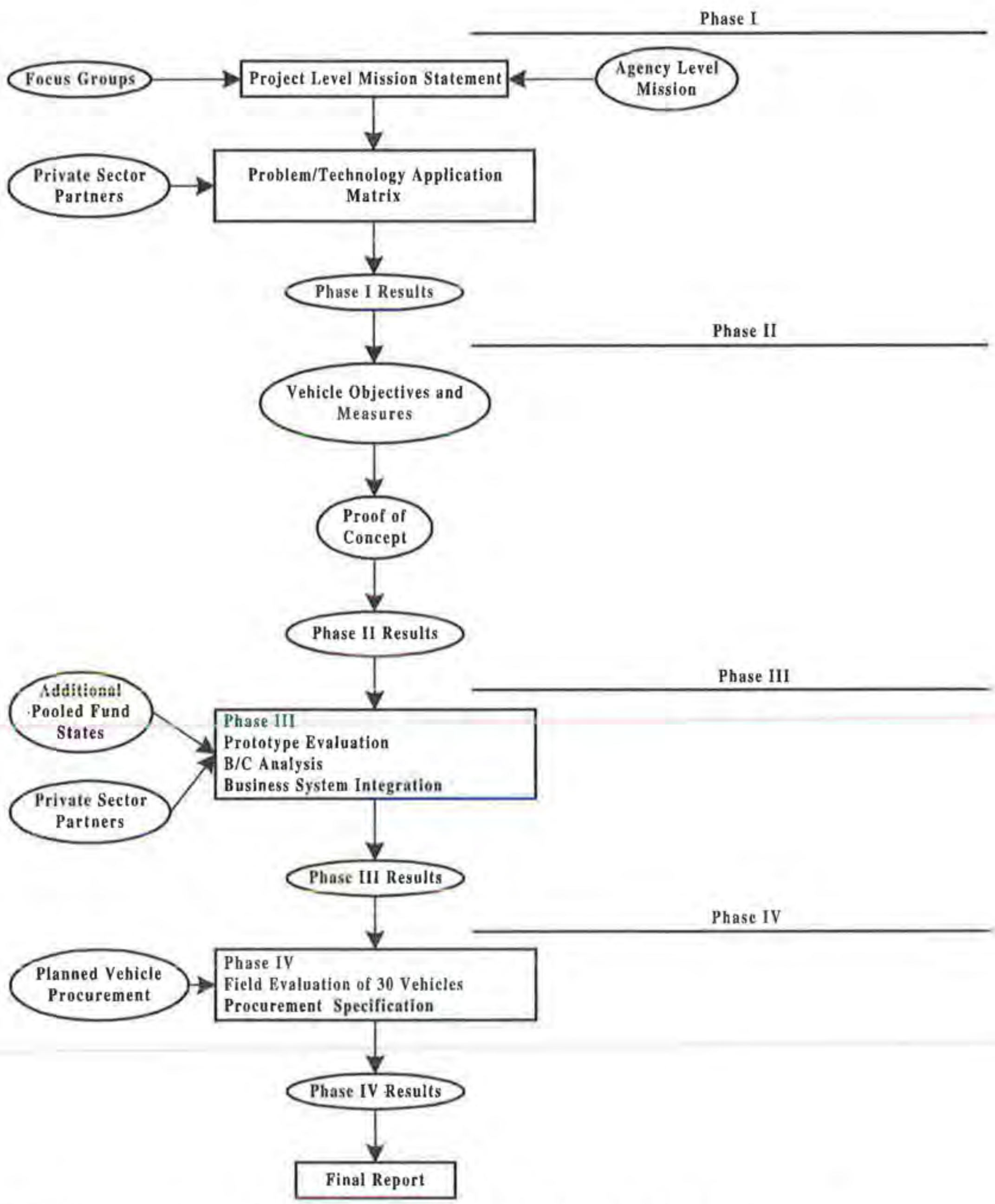


FIGURE 1 Next-generation maintenance vehicle technology: the four-phase approach.

ment capabilities for the Phase III prototype vehicle. Phase II is complete, and the final report, *Concept Highway Maintenance Vehicle, Final Report Phase II,* is on the Iowa State University CTRE website at http://www.ctre.iastate.edu/Research/conceptv/index.htm.

Phase III

The general objectives of Phase III to be achieved in 1999–2000 are to perform proof of concept on newly discovered technologies, establish the functionality of each technology to be implemented, conduct a benefit/cost analysis for each technology, estimate the time to implementation, conduct field evaluation, produce data flow and decision process maps to integrate the concept vehicle functionality in management and ITS systems, and develop draft vehicle specifications for each consortium state.

Phase III will answer these questions:

- Which technologies should be implemented?
- What are the benefits and costs of each technology?
- What is the expected time to implementation?

Sensing roadway surface conditions is being attempted by Norsemeter of Norway using a device called Saltar. The Saltar design is an outgrowth of the evaluation done in Phase II and has been tested at Wallops Island, Virginia, and North Bay, Ontario. Both tests are sponsored by the National Aeronautics and Space Administration and attended by several manufacturers of surface friction measuring devices. The Saltar device did function as expected. The report will be placed on the Iowa State University CTRE website.

Benefit/cost analysis is currently being conducted on the pavement-surface temperature measuring technology. Benefits will be based on estimating the difference between materials distributed knowing the pavement-surface temperature at the vehicle's location and materials distributed based on the pavement temperature measured at a remote road weather information system (RWIS) site. Data are being collected based on interviews with field staff and from databases generated by the vehicle and the RWIS site. Analysis is currently under way.

Phase III also includes conducting proof-of-concept evaluation on a pavement-surface freezing point sensing system. CTRE is currently bench testing the system, supplied by Enator of Sweden.

Phase IV

The objectives of Phase IV are to

- Equip 10 vehicles per state with selected advanced technologies, and
- Conduct field evaluation.

Interfacing with ITS

National ITS Architecture

The Iowa Department of Transportation envisions the concept vehicle functionality fitting into the National ITS Architecture Subsystem and Communications architecture very smoothly. Figure 2 illustrates the placement of the functionality.

Road and Weather Model Interface

As part of the Weather Information for Surface Transportation ITS Field Operational Test, the Iowa prototype maintenance vehicle provided air and pavement temperatures to the Foretell Consortium to assist in the calibration of a new road and weather forecast model. This interface is depicted in Figure 3. It is envisioned that the 10 advanced-technology maintenance vehicles in Phase IV of this research will serve as Foretell's mobile platforms. The vehicles will use National Transportation Communications for ITS environmental sensor station protocol standards to radio air temperatures, wind speeds, pavement data, and maintenance operations reports in real time to Foretell ITS service centers. These service centers will provide the interface between ITS and ITS users, allowing progressive deployment of weather, roadway, and other ITS applications throughout the service center area.

Conclusions

The four-phase research project to develop a new-generation, advanced-technology highway maintenance vehicle began in 1995. The vision was to develop a concept vehicle that would support equipment operators and fleet managers in making more informed and cost-effective decisions based on emerging ITS technology. The approach was to bring technology applications from other industries to the concept vehicle. The customer was brought into the planning process at the very beginning, which is one of the reasons the project has been successful in field testing. The advanced-technology applications have withstood the severity of snow and ice control operations for two winters with only minor problems. Field operators and managers feel the new technology has made their efforts more efficient and effective. The information these vehicles provide to the ITS community is an incidental benefit to the main snow and ice control mission and is used by both the Department of Transportation in its operations management and the ITS service centers.

As new technologies emerge, they will be evaluated and tested using the model developed for this research project.

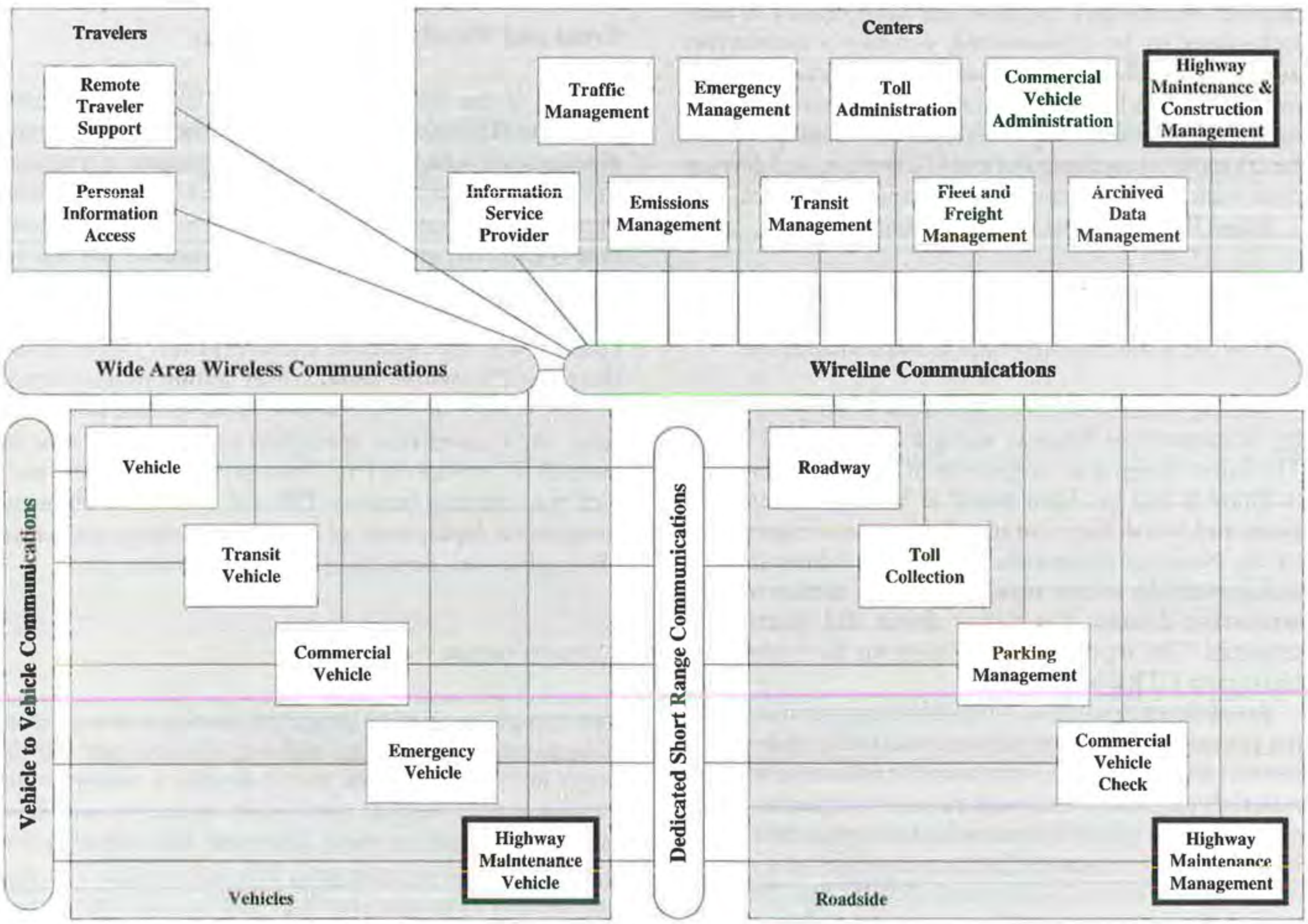


FIGURE 2 National ITS Architecture interface.

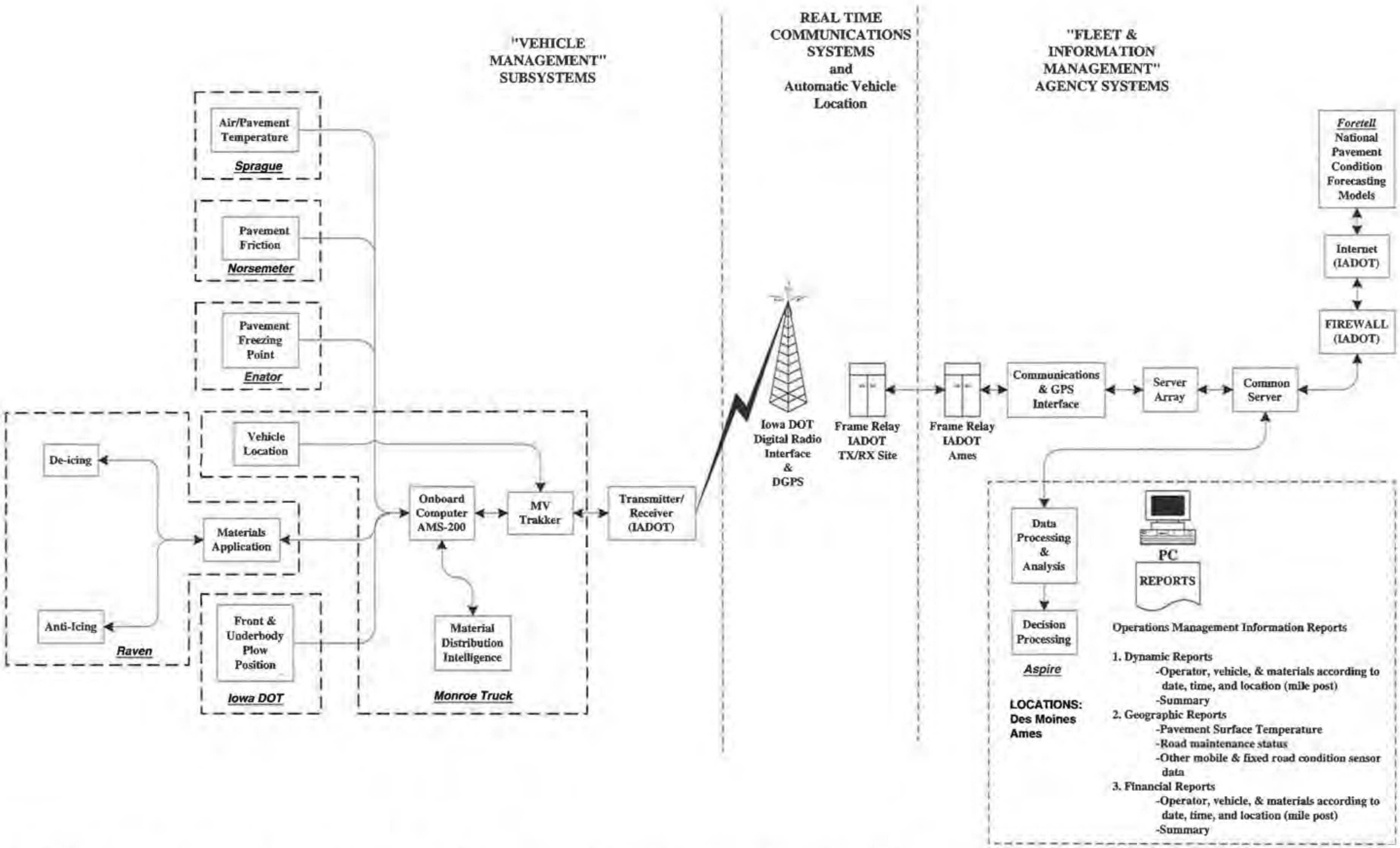


FIGURE 3 Iowa Technologies Network diagram, Phase III concept vehicle (work in progress). Source: Iowa DOT.

Part 8
MAINTENANCE MANAGEMENT

Empowering Employees and the Organization by Implementing and Evolving a Maintenance Management System

Three Years In

Paul Corti

In the past several years, several states have undertaken maintenance management system initiatives characterized by formal, competitive procurements; lengthy project duration; and significant investment of time and resources by both the acquiring organization and the selected provider. A description is given of how Vermont, operating in a resource-constrained environment, has pursued "a path less frequently traveled" to successfully implement and continue to evolve a maintenance management capability that has empowered its employees and has generated value and benefit for the Vermont Agency of Transportation (VAOT). Vermont adopted a strategy of fielding an initial core capability for the Vermont maintenance activity tracking system (VTMATS) and then augmented the core capability through a series of additional releases. VAOT successfully addressed the training and organizational change challenges associated with the implementation and operation of a new system. The challenges VAOT faced are described in terms of time frame (initial operation, first year of operation, and beyond), the benefit and value that have been realized, and the surprises (both unanticipated "wins" and lessons learned). Also addressed are the organizational relationships that have been created or reinforced through the operation of VTMATS and the incentives and empowerment of system users. Use of VTMATS to support maintenance management activities is far greater than initial expectations, and other experiences show how user expectations and perspectives have changed significantly during the past 3 years. The acquisition and resource requirements associated with the Vermont experience are examined in terms of how VAOT has implemented and evolved the VTMATS in a resource-constrained environment using alternative strategies and approaches that are streamlined, yet still yield effective and economical results. How the system is expected to mature and change over time relative to user and organizational expectations also is discussed.

Vermont Agency of Transportation, 133 State Street, Montpelier, VT 05633.

Early in 1992 the Vermont state legislature directed the Vermont Agency of Transportation (VAOT) to pursue the feasibility of acquiring or developing a maintenance management system. An effort was undertaken to research what was available through polling and surveying other states, and visiting and viewing systems. This led to the acquisition of Arizona's PeCoS system. After a couple of years, all the available knowledge and experience from all the stakeholders were incorporated into a request for proposals. Difficulties with the agency's infrastructure and stakeholder turnover also contributed to a resultant system that did not perform as anticipated. At this time, a decision was made to revise the agency strategy to an approach that emphasized the establishment of a core capability that would enable Vermont to determine the cost of doing business and provide a basis for intelligent planning and budgeting. The past 3 years have reinforced the wisdom of being willing to change course; focus on starting with the basics and getting them right; build on successes in a modular, incremental fashion; and allow stakeholder discovery to generate subsequent successes and organizational buy-in. The sections that follow describe the

Vermont experience with the Vermont maintenance activity tracking system (VTMATS) in pursuing "a path less frequently traveled" and the value and benefit realized by VAOT and its employees.

Arriving at the Present Situation

When VAOT decided to revise its strategy, it examined the experience of the prior year(s) and developed an approach that would leverage its successes as well as capitalize on opportunities to do things differently. The strategy had to be able to address the basic, core capabilities and allow the organization to retain the ability to adjust to change. The direction that was set addressed the project from three perspectives, each of which was essential to the overall success of the system: the user perspective, the management perspective, and the technological perspective. Each is summarized below.

User Perspective

Part of the revised strategy involved revisiting the VTMATS effort from the user perspective. One of the primary goals was to get the basic capability in the hands of the end users to capture work done and resources consumed so that data capture would be in process while other capabilities were being developed. Two of the key considerations were (*a*) to recognize the end user as the key element of data capture, data entry, and data integrity; and (*b*) to limit the amount of data that the user must capture while making entry as easy as possible. In addition, it was recognized that the best chance for success was to create a positive incentive for the user to provide quality data. Time reporting and time-sheet generation through the VTMATS provided that incentive.

Management Perspective

Gaining management buy-in is important, but retaining that support is even more important. This was achieved through the revised strategy by focusing on the core capabilities and getting them correct. This led to a series of "early wins" with respect to the core capabilities and generated the momentum required to retain management support. The existence of policies, procedures, and activity standards from the earlier effort proved to be a plus in saving time and effort and enabling work to progress at a rapid pace in generating the early wins. Finally, the decision-making process was streamlined by empowering the project manager to make binding decisions for the effort. The overall management structure was retained, but the project manager was granted much more authority to act, which yielded tremendous savings in time and resources.

Technical Perspective

Among the technical considerations, there were two keys to the overall approach. The first was a decision to take a broad view of designing for the long haul but implementing for the near term with basic/core capabilities. The second key was candidly assessing the limitations and constraints of the existing environment and working within those boundaries. In the case of the former, a strategy was adopted to perform design with a view toward the future, which meant developing an overall blueprint for the system even though detailed design and development would involve separate functions and incremental capabilities. For the latter, a candid assessment of the current infrastructure identified the existing strengths to leverage as well as the limitations to offset. The results were a flexible, modular design that could be implemented in separate increments and an architecture that could be adapted to the technical environment without being tied to a particular technology or unique environment. Other elements of the technical perspective included the following:

- Using rapid application development alternatives and techniques was pursued.
- Deciding to use a small, focused, dedicated development team with short and direct lines of communication resulted in a high percentage of quality code that did not require significant rework.
- Establishing and maintaining close control over the development environment and the data and following basic development standards preserved the desired level of design flexibility.
- Recognizing and making data transfer an important design consideration (knowing the infrastructure capabilities and limitations) resulted in a very efficient application.

First Things First

Recognizing that the real value was tied to the data, the decision was made to "follow the money" by implementing a daily work reporting capability that would capture the labor, equipment, and material used to perform work and the associated work accomplishment. Figure 1 represents the latest review of the daily work report (DWR) screen. The information on the DWR was arranged by organizational units (down to individual workers) and identified work activities performed at specific locations. Implementing this capability first put emphasis on the largest group of users and at the same time began capturing data that would be needed later to support other capabilities (e.g., planning, budgeting, and year-end reporting as well as seasonal reporting). Also, a decision was made to conduct one-on-one visits with users to load the application, perform training reinforcement, and obtain

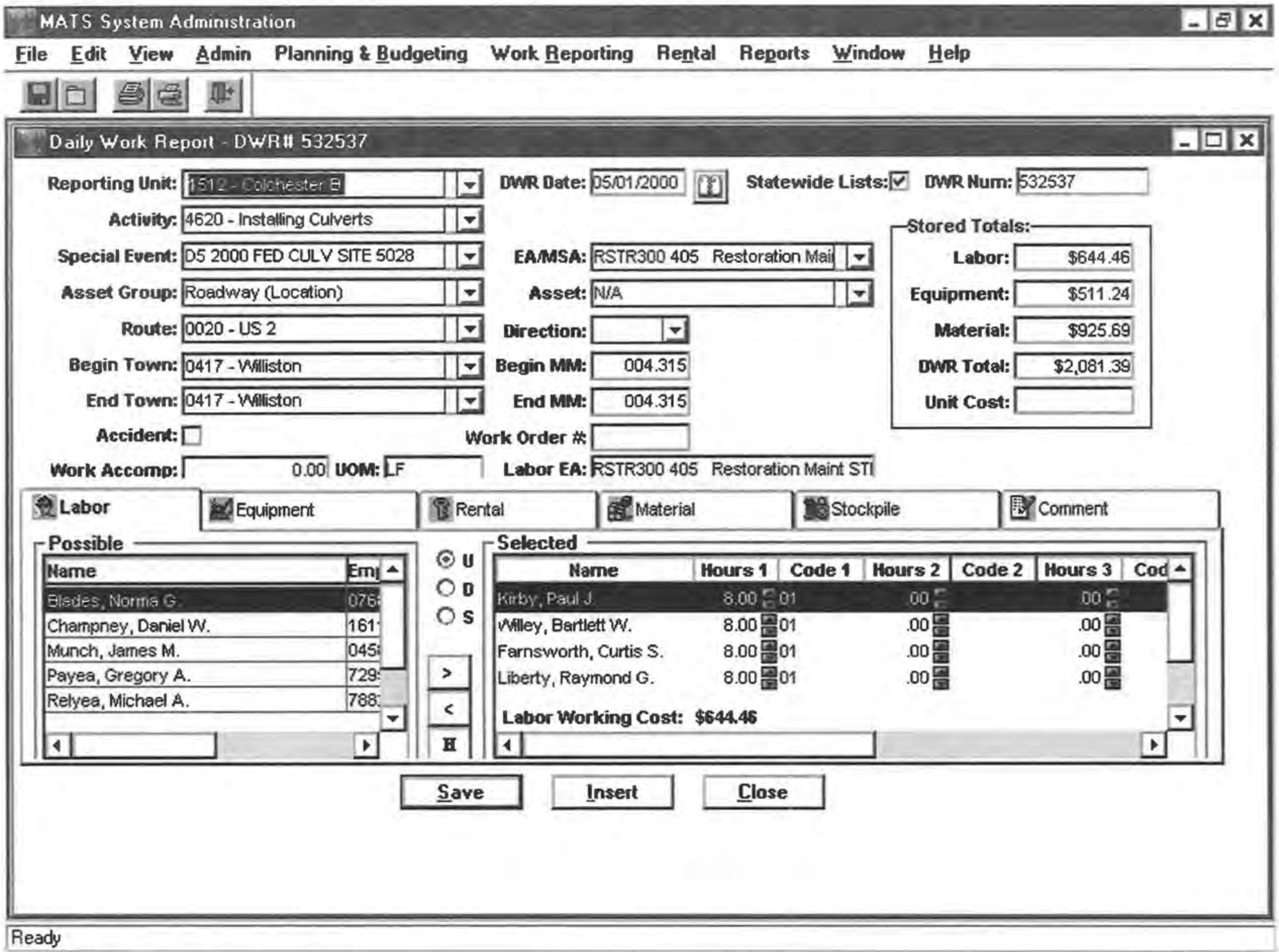


FIGURE 1 Daily work report screen.

immediate feedback from initial users. The payback on this decision was substantial because the users understood what they were doing with the system and why, rather than simply responding to a system prompt. This was possible because of the reasonable number of users and workstations and the willingness of several maintenance personnel to assume a support role for the application. Over time, the support role that began as an additional duty became a full-time role for some, and for others that role provided a means for career transition and upward mobility within the organization.

The initial capability also included DWR accomplishment reporting and unit and statewide rollup reporting for the data associated with DWR. A detailed DWR listing by time frame is shown in Figure 2, and Figure 3 presents a statewide summary by district. This was immediately followed with the ability to generate employee time sheets from the data in the system. While users were continuing to report on a daily basis, the next increment was being prepared for release. It included

- Stockpiles,
- Special events,
- Expenditure accounts, and
- Rental contracts.

These capabilities were released in the spring of 1998. By fall of 1998 the winter storm report was ready before the upcoming winter season; and in the spring of 1999, Planning and Budgeting was ready to be fielded before the beginning of the next fiscal year in July 1999. In each case the implementation choices were made by weighing the benefit of what would be implemented against the value to the users and to the maintenance program.

At the same time that these incremental capabilities were fielded, there was a growing base of data available for use in the system. In late 1997, there were approximately 65,000 records. That number grew to a cumulative total of 360,000 records in 1998, 750,000 in 1999, and 1,280,000 to date in 2000.

How Vermont Uses the Data

With an expanding body of data available, opportunities began presenting themselves to the Maintenance Division, the districts, and the units for data analysis and reporting. It was no longer necessary for users or managers to wait for end-of-month, quarterly, or yearly reports to be generated to review productivity, cost, or accomplishment. Information was available on demand, as shown in the architecture in Figure 4. It also is important to recognize that the edits and error checking accomplished during source data entry resulted in better data quality. When it became known that a database of quality information was available, the Maintenance Division began receiving requests for information for accounts from many other organizations and individuals. Some of the more significant uses of the data include the following:

- Adjusting and refining maintenance activity standards based on actual experience and even tailoring the standards based on local differences among units;
- Calculating unit costs for all maintenance activities, and comparing and analyzing the unit costs throughout the state;
- Capturing data and reporting on special events such as individual snowstorms, floods, and ice storms;
- Developing and managing budgets and allocations to districts and units;
- Developing annual program goals and objectives and reporting progress and results against the program plan;
- Comparing annual accomplishments and expenditures (unit-level and rollup reports);
- Comparing self with other organizational elements;
- Responding to inquiries from the organization, management, and the public (e.g., press and citizens);
- Performing federal reporting (system outputs accepted as valid reporting for the Federal Emergency Management Agency requirements);
- Performing insurance reporting and accident reporting;
- Managing expenditures and expenditure rates for activities and organizational units; and
- Reconciling central garage equipment usage with changes in actual equipment readings.

Many more possibilities will exist as more data become available and as additional capabilities are implemented.

Opportunities Realized in Vermont

Vermont is approaching 3 full years following the implementation of VTMATS and has accumulated an expanding reservoir of quality, statewide maintenance data. VAOT knows what work was performed, what the work cost, where the work was performed and by which unit, and what was accomplished. During this time, the accumulation of small wins has produced a major victory for the agency and has substantiated the wisdom of the strategy pursued. Three years in, Vermont is able to

- Produce maintenance accountability and accomplishment reporting, by organizational unit or by event, for any time period;
- Prepare performance objectives and goals for the workforce and plan, budget, and monitor progress against the objectives;

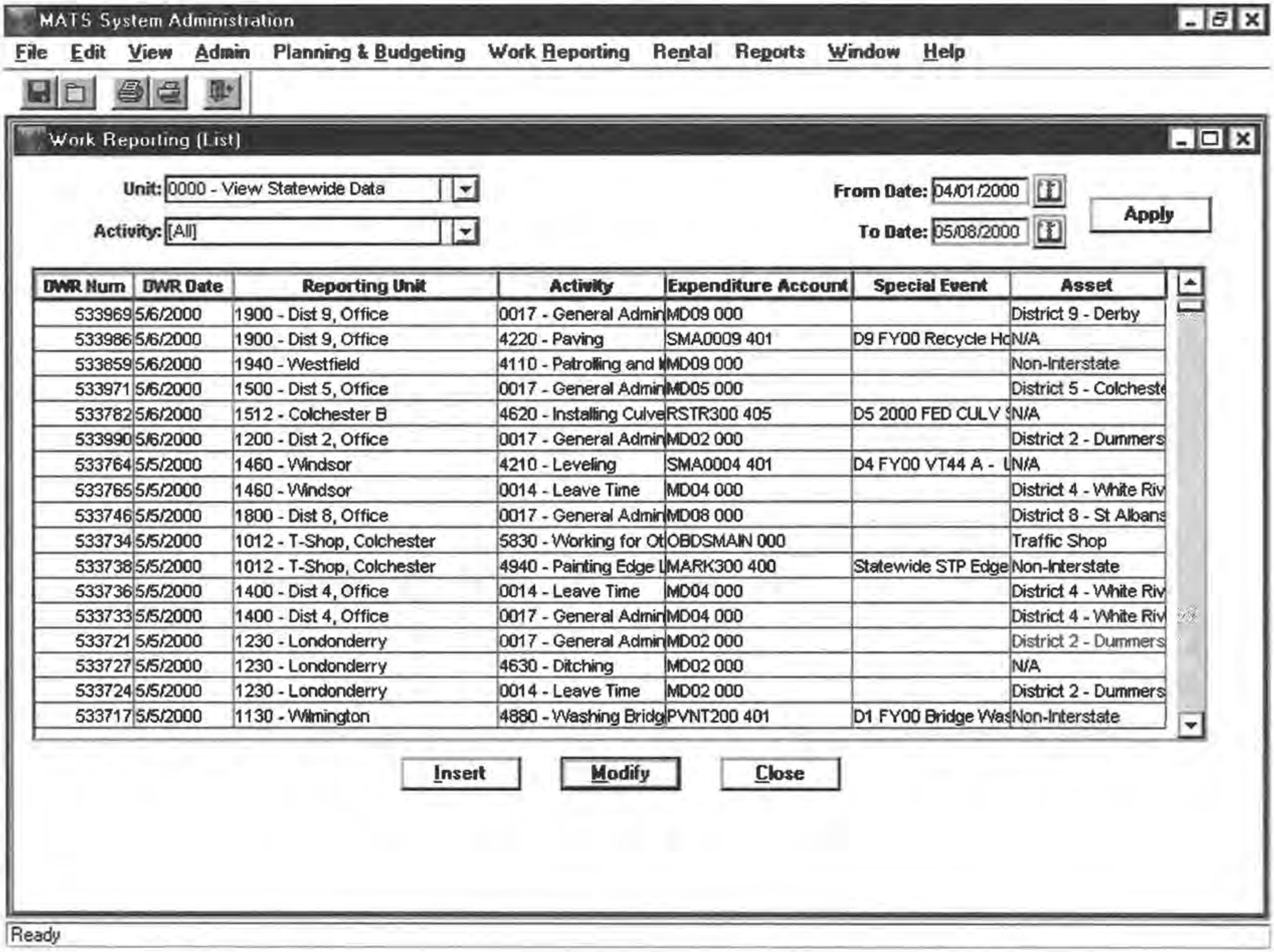
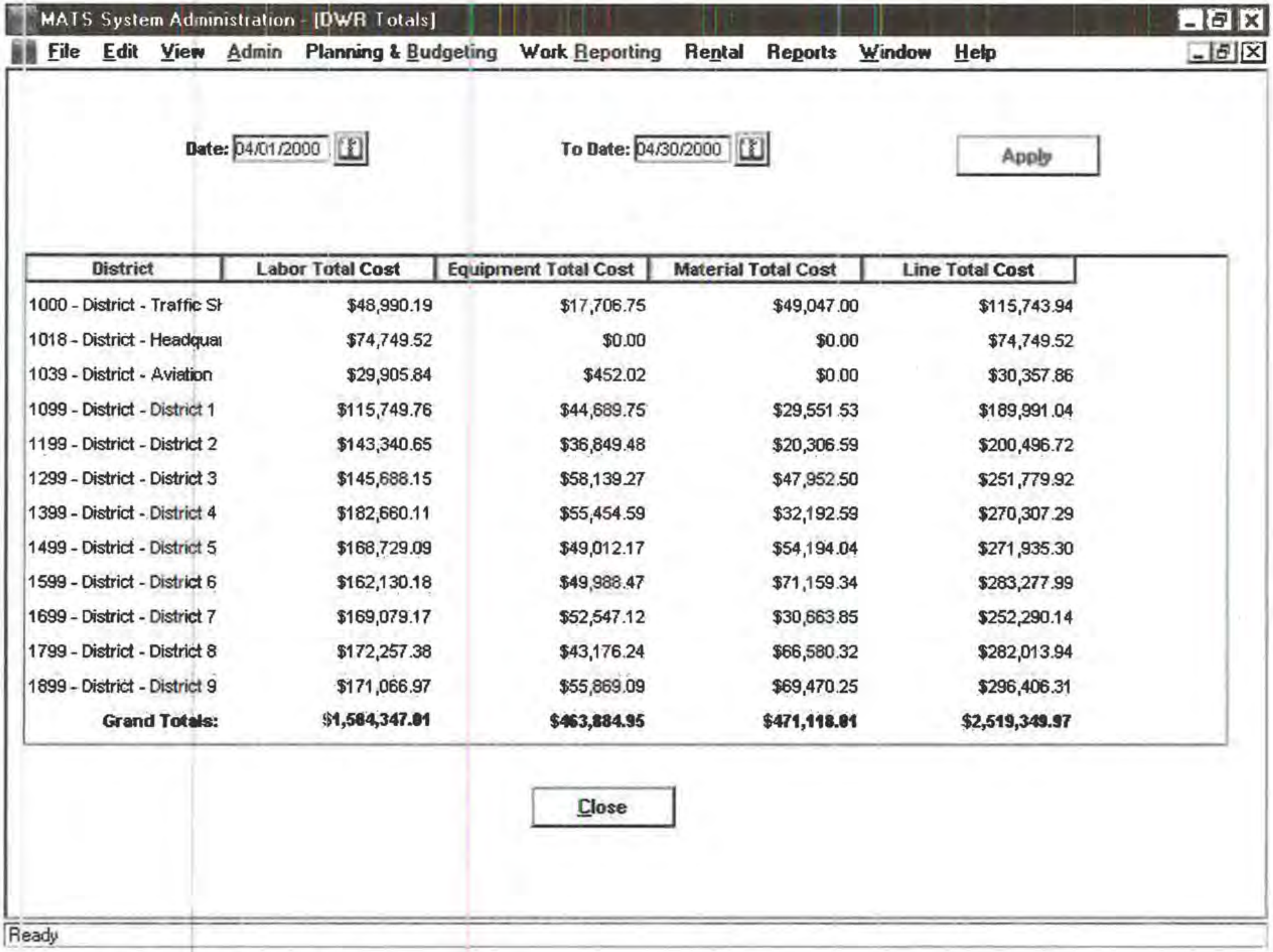


FIGURE 2 DWR detailed listing by date.



District	Labor Total Cost	Equipment Total Cost	Material Total Cost	Line Total Cost
1000 - District - Traffic St	$48,990.19	$17,706.75	$49,047.00	$115,743.94
1018 - District - Headquar	$74,749.52	$0.00	$0.00	$74,749.52
1039 - District - Aviation	$29,905.84	$452.02	$0.00	$30,357.86
1099 - District - District 1	$115,749.76	$44,689.75	$29,551.53	$189,991.04
1199 - District - District 2	$143,340.65	$36,849.48	$20,306.59	$200,496.72
1299 - District - District 3	$145,688.15	$58,139.27	$47,952.50	$251,779.92
1399 - District - District 4	$182,660.11	$55,454.59	$32,192.59	$270,307.29
1499 - District - District 5	$168,729.09	$49,012.17	$54,194.04	$271,935.30
1599 - District - District 6	$162,130.18	$49,988.47	$71,159.34	$283,277.99
1699 - District - District 7	$169,079.17	$52,547.12	$30,663.85	$252,290.14
1799 - District - District 8	$172,257.38	$43,176.24	$66,580.32	$282,013.94
1899 - District - District 9	$171,066.97	$55,869.09	$69,470.25	$296,406.31
Grand Totals:	**$1,584,347.01**	**$463,884.95**	**$471,118.01**	**$2,519,349.97**

FIGURE 3 DWR statewide summary by district.

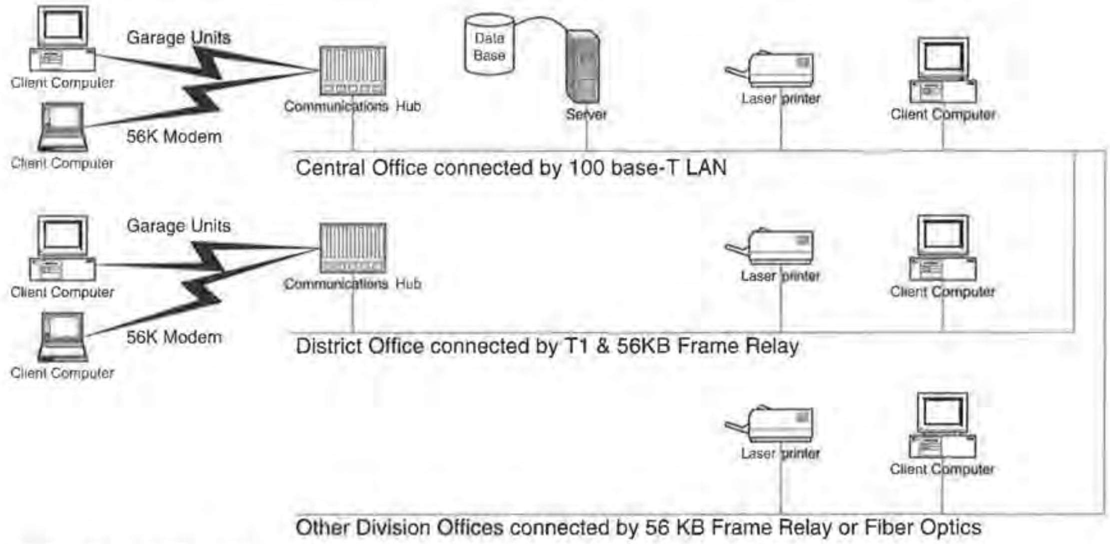


FIGURE 4 VTMATS production environment.

- Minimize the burden on the end user for data entry while maintaining a high level of accountability and data management;
- Respond rapidly to inquiries from senior management, the legislature, and municipalities with accurate, detailed information;
- Demonstrate a knowledgeable, empowered user community that understands what they are doing with the system and why, rather than simply responding to a system prompt;
- Gain support for future enhancements based on the value being delivered by the current capabilities of VTMATS;
- Interface with the financial system for equipment usage, expenditures, labor costs, materials costs (including federal projects reporting), and rental contracts;
- Provide time reporting and time-sheet printout;
- Prepare proactive planning and budgeting based on documented activity standards, unit costs, and levels of service;
- Provide accurate materials management (stockpile management); and
- Continue moving forward with an overall strategy based on design flexibility and architectural/technological independence that permits VAOT to leverage its strengths and accommodate its constraints.

Additional value is realized through the ability to provide both detailed and summary information at the unit, district, and statewide levels empowering users and managers throughout the agency. Overall there is less reliance on paper and an increasing use of electronic transfer and sharing of information. A positive indication of this general empowerment is the fact that the number of users doubled between the first and second years of operation with many requests coming from nonmaintenance personnel. Another example of empowerment occurred during a recent outbreak of a computer virus. VAOT was able to assist in the "cleanup" effort by mobilizing the extended VTMATS support staff to visit every computer and perform the necessary diagnostic work; and through the use of special events, VAOT was able to identify the costs of this effort.

Where Do We Go Next?

Three years in, Vermont finds itself in a position to continue moving forward, capitalizing on the credibility achieved and the victories gained rather than trying to overcome hurdles, obstacles, and setbacks. The near-term decision is to stay the course and follow the strategy that has produced the successes to date—specifically, to build on the past 3 years by adding and implementing more capability within VTMATS by weighing the benefit and value of each capability to the users and the maintenance program. Of paramount importance in pursuing this path is retaining the ability to adjust to change and capitalize on opportunities that arise. Preserving design flexibility and architectural independence and understanding our limitations are the keys to future success for Vermont.

Figure 5 summarizes the direction followed from a technical perspective. Some of the functional and business initiatives that are currently under consideration for "where we go next" include

- Building and expanding on inventory information;
- Creating linkages to both bridge and pavement management;

	Startup	Current	Future
Database Server			
Make	IBM PS/2	Compaq Proliant 3000	Compaq Proliant 3000
Processors	1/150 MHz	2/500 MHz	2/1000 MHz
RAM	208 MB	4 GB	4 GB
Hard Drives	2/10 GB	3/24 GB	5/90 GB
Operating System	NT 3.51	NT 4.0	NT 2000
Databases			
Databases	SQL Server 6.0	SQL Server 7.0	SQL Server X.X
			Oracle Y.Y
Users			
Modem	40	35	30
LAN/WAN	30	75	90
Other	0	0	100
Other Servers			
Other Servers	NA	NA	Web
			Application
Client Computers			
Make	Compaqs	Compaqs	Any
Processor	33 MHz	266 MHz	Any
RAM	8 MB	32 MB	Any
Operating System	Windows 3.1	Windows 95	Inter/Intranet capable
		Windows 98	
		Windows NT	

FIGURE 5 Technical environment.

- Refining and creating more comprehensive interfaces to the finance, human resources, equipment, environmental, and agriculture communities;
- Developing linkages to data warehouse and geographic information system initiatives;
- Providing Internet access to selected maintenance data;
- Discovering additional uses for the data through proactive "data mining"; and
- Developing partnerships with other state transportation departments and the federal community to share software and data and lessons learned.

Viewed as a whole, these initiatives might seem overly optimistic, but based on the results of the past 3 years it is believed that having a strategy of creating incremental, value-based capabilities and following it will continue to produce major victories for Vermont.

Experiences in Implementing New Maintenance Management Systems

Petri Jusi and Jan Juslén

The Highway Development and Management Tool, HDM-4, was in the beta testing and pilot trial phase during 1998 and 1999. The Finnish National Road Administration (Finnra) has been testing the programs, with all early versions providing feedback for further development at the University of Birmingham. Now that Version 1.0 of the program has been released, Finnra's experts are using it in international projects in Europe, Asia, Africa, and Oceania. Two projects, which were conducted in totally different environments, are described and evaluated. Case 1 was carried out in Northwest Russia in 1999, in cooperation with local road authorities and consultants from Ramboll, DHV, SPEA, and Finnra. This pilot was one of the first carried out in northern freezing climates. Case 2, an ongoing Finnra project in Papua New Guinea, started in 1998. Its goal is to establish a road asset management system for the National Road Administration in Papua New Guinea. The project also includes road inventory surveys based on Global Positioning System and international roughness index measurements. The main output of Case 1 is a highway rehabilitation master plan (HRMP), which was prepared for attracting investors to participate in developing the road network in Northwest Russia. The main output for Case 2 is to inventory the road network, establish a road databank, establish a road asset management system with geographic information system, and create an HRMP for 5 years. These cases and all the phases of implementation of the new management system are evaluated. The most important goal of the projects is to ensure that local experts are fully capable of using the system. Training played an important role in every step, and training strategies were ambitious. The major lessons learned during the projects were as follows: (*a*) the time needed for implementation of a new system should not be underestimated; (*b*) quality of data is a key issue; (*c*) the need for personal contacts with local experts during the project is high; and (*d*) training should be organized in all phases of the project.

Finnish National Road Administration, Export Services, P.O. Box 8, FIN-00521 Helsinki, Finland.

The Highway Design and Maintenance Standards Model (HDM-III) developed by the World Bank has been used for more than two decades to combine technical and economic appraisal of road projects. The International Study of Highway Development and Management has been carried out to extend the scope of the HDM-III model and to produce the Highway Development and Management Tool (HDM-4).

The scope of this new tool has been broadened considerably beyond traditional project appraisals to provide a powerful system for the analysis of road management and investment alternatives in various technical, economic, and environmental circumstances, including cold climate areas, which were omitted from the previous versions of the HDM.

The analysis methodology in this project has followed HDM-4 project analysis. Project analysis is concerned with the evaluation of one or more road projects or investment options. The application analyzes each road link or section with user-selected treatments, with associated costs and benefits projected annually over the analysis period. Economic indicators are determined for the different investment options.

Project analysis is used to estimate the economic or engineering viability of road investment projects by considering the following issues:

- Structural performance of roads;
- Life-cycle predictions of road deterioration, road works effects, and costs;
- Road user costs and benefits; and
- Economic comparison of project alternatives.

The model simulates, year by year, the road condition and resources used for maintenance of each road section, under each strategy, as well as the vehicle speeds and physical resources consumed by vehicle operation. After physical quantities involved in construction, road works, and vehicle operation are estimated, user-specified prices and unit costs are applied to determine financial and economic costs.

Relative benefits against a base case (do nothing or do minimum) are then calculated for different alternatives, followed by net-present-value and rate-of-return computations. The sections can then be sorted by net present value of benefits or by internal rate of return to produce a ranking list of the most beneficial candidates for investments.

The benefits of maintenance are mainly accrued from improved road roughness, which is the main factor affecting vehicle operating cost (*1*).

CASE 1: NORTHWEST RUSSIA

Study Area and Main Objectives of the Project

Northwest Russia includes the regions of Arkhangelsk, Kaliningrad, Kirov, Leningrad, Murmansk, Novgorod, Pskov, and Vologda. It also includes the city of St. Petersburg and the republics of Karelia and Komi as well as the autonomous Okrug of Nenets. Northwest Russia covers about 10 percent of Russia, both its population and its territory.

The study area includes the oblasts of Arkhangelsk, Leningrad, Murmansk, Novgorod, and Pskov as well as the republics of Karelia and Komi. The major city in the area, St. Petersburg, situated in the eastern part of the Gulf of Finland with a population of 4.8 million, is not included in the study area, nor are the Kaliningrad and Kirov oblasts. The autonomous Nenets also is not included. The total study area is 1.7 million km^2 and has a population of 9.2 million (see Figure 1).

The main output of the pilot trial was a highway rehabilitation master plan (HRMP) for the federal and local road network of Northwest Russia, which was prepared for attracting investors to participate in developing the road network there. In the HRMP, the road projects were prioritized with the HDM-4 program. Prioritizing in HDM-4 was done in the project analysis part of the program. Project analysis is based on comparing the benefits

FIGURE 1 Study area map, population, and population density (Case 1).

and costs of an individual project. With this process every project has a benefit/cost ratio, and the priority list implements the most beneficial projects first. Outputs of the project were

- Systems and procedures for the collection, analysis, dissemination, and application of road-related data;
- Trained staff for these systems and databases;
- An assimilated highway management model, the HDM-4 program in Road Directorate 9 (RD9), and the subjects; and
- A regional highway rehabilitation master plan for 2000 and later.

Following is a list of detailed project activities: (*a*) review of road organization setup and current data collection methods, (*b*) identification of the significant road network and division of the network into sections, (*c*) development of a road traffic database for the road section data, (*d*) introduction and installation of HDM-4, (*e*) calibration of HDM for prevailing conditions, (*f*) data compilation and data quality control, (*g*) preparation of a highway rehabilitation master plan and support for an investors' conference, (*h*) reporting, and (*i*) training and knowledge transfer.

The HDM-4 work of the project consisted of the following phases. These phases basically are done in every process in which the goal is to produce a priority list of projects with a maintenance management system: (*a*) data collection procedures and data compilation, (*b*) data input, (*c*) road characteristics, (*d*) road condition data, (*e*) traffic data, (*f*) construction and maintenance history, (*g*) calibration, (*h*) training, (*i*) analysis, and (*j*) evaluation of results. These phases are described below.

Data

Data Collection Procedures

Data collection for HDM-4 was done with the assistance of regions and republics. The input of RD9 also was significant. Because the data collection from existing data was done in the winter, the new measurements were not carried out. Thus there is a need for new measurements in the future, when local authorities update the master plan. The submitted data consisted of compiled existing road condition and traffic information data, as well as road construction and maintenance history information when it was available. For the data not available, the road authorities in each subject drew current best estimates.

In a country where a road data bank (RDB) is already functioning, these data could be transferred directly from the RDB to HDM-4. If there is no RDB, it is possible to use the HDM-4 program as an RDB. It is vitally important that the road condition data and traffic information data be updated regularly because the outputs of any maintenance management system are based on basic data in the program. If the input data are not correct, the results are not usable. The process of data collection is illustrated in Figure 2.

Data Input

The HDM-4 experts of the project carried out the data input for the HDM-4 program. In the future, the concept is that local experts in the regions and republics will accomplish the data input. Data inputting was done manually because it was not possible to transfer the data directly from the RDB. The first phase of data input was sectioning of the road network for the HDM-4 program. This was done in every oblast and republic based on homogenous sections. When the sections were input to HDM-4, the road condition, traffic information, and construction and maintenance history information were input to every homogenous road section. The sections are specified by road name, road number, section address, and information on section nodes.

In selecting the section break points, the following guidelines were followed. A road was broken into sections in main intersections, where a major change in traffic volumes is possible. A section was further broken if the section seemed to become too long. In subjects, the number of sections varied from 41 to 120 (Murmansk, 41; Karelia, 60; Arkhangelsk, 118; Leningrad, 120; Pskov, 50; Novgorod, 60; and Vologda, 60).

After revision of sectioning, the total number of sections in the HDM-4 program was 678. The data were manually input into HDM-4 as they were submitted or as they were read from the database (excluding the roughness transformations). In the future, data retrieval should be developed to be as easy as making a query over an Internet connection.

Road Characteristics

To keep the data collection effort at a reasonable level, only the main road characteristics were requested from

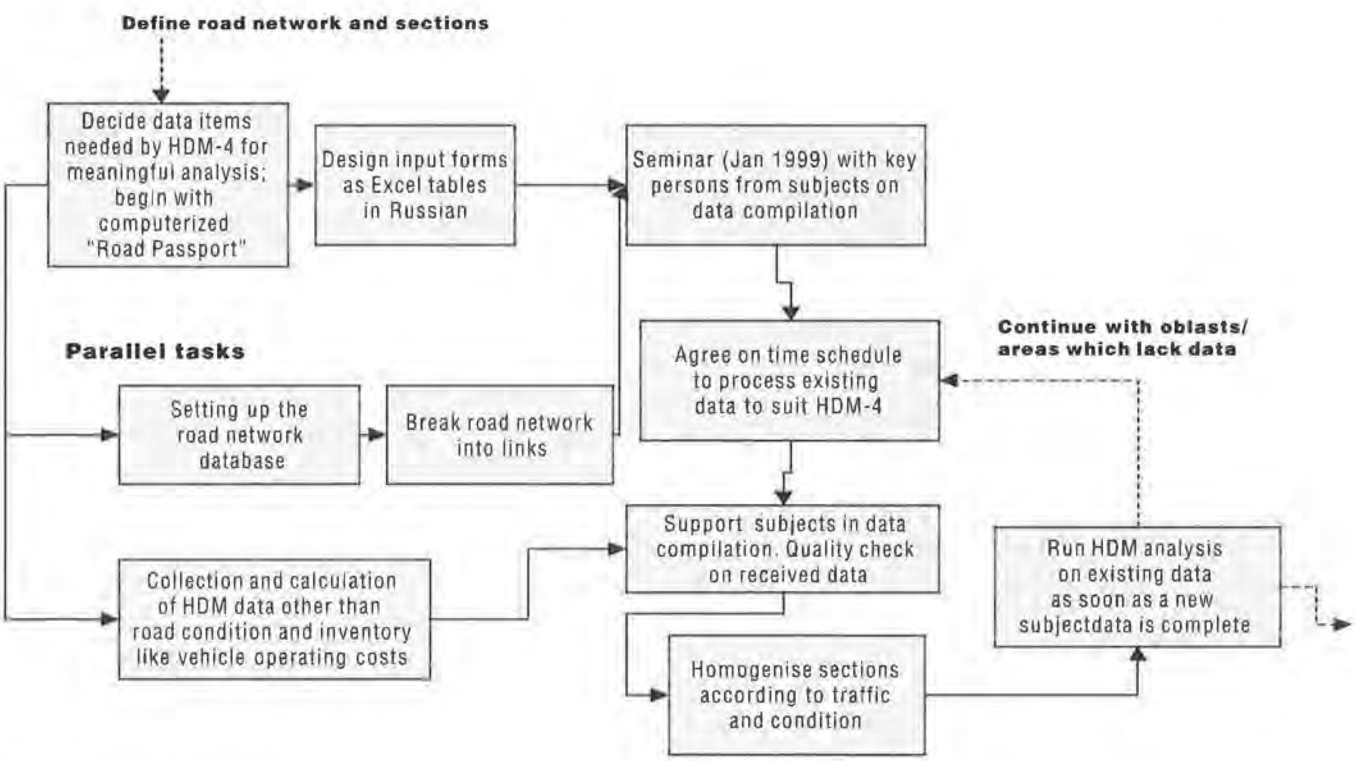


FIGURE 2 Data collection process.

the subjects. The characteristics listed below are enough for a preliminary analysis:

- Administrator of the road section (federal, territorial, municipal);
- Width of the road in meters;
- Number of lanes;
- Surface class (bituminous, unsealed, concrete);
- Surface material (description of the material and/or surfacing method used);
- Pavement type (technical information on combination of subgrade and pavement);
- Descriptions of thickness and so on, depending on surface class;
- Flow type, one-way or two-way traffic;
- Length of section in meters;
- Curvature (light or heavy);
- Hilliness (light or heavy); and
- Pavement history (information on past construction and maintenance operations).

Additional information, such as information about accidents, was requested, using the accident costs in the cost/benefit calculation. These figures were not submitted in full and therefore were not used in the HDM analysis. Basically the accidents should also be one part of the analysis. The cost of accidents is also a topic that must be considered before using accident information in the analysis.

Road Condition Data

All the road condition data were not available, and it was not possible to measure the condition of sections to make the compilation of data as easy as possible. Therefore defects were classified using a four-level scale, where "A" meant excellent condition and "D" bad condition. The classes were used when no measured data existed, as was the case for most of the territorial network. The condition data items that were requested are listed below.

- Roughness, either as international roughness index (IRI) (millimeter/meter) or as a value or an estimated class A–D; and
- Defects, either as a value or an estimated class A–D:
  - Cracking as percent of pavement area,
  - Raveling as percent of pavement area,
  - Potholes (number of potholes per kilometer),
  - Edge break (meters per kilometer),
  - Rut depth (millimeters),
  - Benkelman beam deflection or falling weight deflectometer deflection, and
  - Survey year.

Roughness describes the class of ride quality, which quantifies the subjective feeling of persons travelling along an uneven road.

A comparison of the data supplied by the subjects with existing kilometer-based data on federal roads was made. This comparison made it possible to assess which parts of the sections have such significant differences in condition data that they need to be analyzed separately. Subjects were asked to supply information on found discrepancies possibly caused by the latest maintenance actions or by incorrect data in the database.

The roughness of the data submitted by RD9 has been measured using a bump-integrator, according to the standard VSN-21-84 or according to GOST norms. The VSN was transformed into the standard IRI values. For future preparation of the road master plan, the condition measurements should be done regularly.

Traffic Data

Traffic data were requested in the form of average annual daily traffic. These data were chosen because they usually are available in all road authorities. European Union experts also knew that, with the current method of traffic data collecting, there could be no reliable estimates for seasonal variation.

The traffic flow was divided in three vehicle classes in the HDM-4. The first class consists of cars and light trucks with a maximum weight of 6 tons. In practice all these cars are two- or three-axial. The second class includes trucks weighing 6 to 10 tons and buses. The third class includes all vehicles with a weight of more than 10 tons. These classes were aggregated from the current data collection forms to represent the typical composition of traffic.

Traffic data sources were

- Information from the automatic traffic counters,
- Information from the federal highway administration database, and
- Estimations of local experts.

The traffic data, especially the number of heavy vehicles, appeared to be very different from the traffic data used in the Western countries. In several link sections, the majority of traffic flow is of heavy vehicles, which is rare in Western countries, where car ownership is more common. It is expected that the development of car ownership will change the flow type in upcoming years.

History of Construction and Maintenance of Road Sections

Information about construction year and other maintenance operations years also should be input in the HDM-4 program. This information was basically available. It includes last reconstruction or construction year, last rehabilitation year, last resurfacing year, and last preventive treatment year for each road section.

Calibration of HDM-4 for Northwest Environment

Internationally accepted default models for climate, road deterioration, maintenance effects, and road user effects are included in the prerelease HDM-4 package. These models have to be calibrated to local circumstances. In the calibration phase of this study, the lowest level (1 of 3) of calibration was carried out, which included the collection of road data from existing sources, with no additional data collection. HDM-4 default values were adopted for data items not available, and the calibration of the most sensitive parameters with best estimates and desk studies was executed (*2*).

The calibration in the project was based on information from local experts and from the road condition data. The problem was that the historical data on road conditions were not available for every section. Therefore it was somewhat problematic to check the deterioration of the roads.

The first calibration was done for the models available in the beta 3.0 version in June 1999. Thus the results of HRMP reflect that situation and not the situation of the models in the prerelease version at the end of July 1999, or any more recent version of the HDM-4. Therefore the calibration of all models always must be checked before the next analysis.

Results

The main result from the HDM-4 run was a priority list of projects. The projects are prioritized by benefit/cost (B/C) ratio. Benefits are based on savings in vehicle operating costs and in travel time. With this indicator, it is possible to get listed maintenance works from the HDM-4 program in every section. The program gives the costs of every operation, and it is also possible to include a budget limit.

In the project, the proposal for the master plan consists of nearly 900 km of the road network. Common to all prioritized sections is that they show high economic benefits. In most cases, the benefits of the rehabilitation are several times larger than the planned invested costs. Results are illustrated in Table 1.

The work plan also included a requirement that all subjects comment on the presented proposal for the HRMP. The expertise of the local experts in defining the needs of road rehabilitation is needed to approve the results of economic analysis. The comments were compared with the HRMP results. In most cases, the subjects agreed with the results, although some individual differences were found. These were mainly due to missing data or misinterpretation of data.

TABLE 1 Results in Karelia Republic

Road Section	Beginning and End Kilometers	Length (km)	Cost (thousands of rubles, 1991)	Net Present Value/ Capital Costs
Territorial roads				
A128, Hiitola–Sortavala	73–91	18	134	5.72
A128, Hiitola–Sortavala	208–260	52	2,423	5.47
Total		70	2,557	
Federal roads				
M18, Spb–Murmansk	425–430	5	374	4.86
M18, Spb–Murmansk	435–478	43	11,924	4.42
M18, Spb–Murmansk	384–397	13	3,586	4.27
M18, Spb–Murmansk	367–384	17	4,648	3.91
M18, Spb–Murmansk	347–363	16	971	3.70
Total		94	21,503	

Training

Translation of the system into Russian was one of the key issues of the project. It was only a preliminary version of the translation, however, and the translation work was still ongoing in January 2000. Without translation, the training would have been impossible.

Training is the most important phase in implementing a new maintenance management program in a new country. If the consultant executes all the work without clear commitment to the project by local authorities, the benefits of the project are not sustainable. A proper training program and an on-the-job training consultant ensure that, when the current project is completed, the local authorities can continue running the program each year and get the most benefit from it.

In this project the training was implemented with several training seminars and sessions. The main training was carried out in an HDM-4 training session in the Pavlsovsk Training Center in St. Petersburg in September 1999. In that seminar, all the local experts who would be responsible for year-to-year programming with HDM-4 software were present. The seminar's main goal was to make sure that the local experts had adequate knowledge of how to use the program. This was done with normal presentations and especially with case studies, in which the trainers input the data by themselves and ran project analysis cases, just as they will when carrying on their year-to-year planning work in their road organizations.

Naturally, more training and practice are needed in the future in order to ensure sustainability. Establishing an HDM-4 user group in this area was discussed and recommended.

Case 2: Papua New Guinea

Introduction

The Finnish National Road Administration (Finnra) has been responsible for the implementation of a road asset management system (RAMS) project in Papua New Guinea since October 1998. The project is financed through a grant by the Asian Development Bank and will be completed in September 2000. This presentation was prepared when approximately 70 percent of the project had been implemented and, therefore, contains results that are only preliminary in nature.

The road asset management system established under the project is the foundation for systematic and sustainable management of Papua New Guinea's road network and contains basic data on the physical characteristics of roads, traffic data, and cost data. These data are supplemented by regular condition surveys as well as a system for planning maintenance operations and carrying out economic analysis. RAMS also provides illustrative methods for presenting data to decision makers. RAMS is subordinate to national development plans, which set forth all policy and strategic issues, set maintenance and development objectives, and indicate the financial resources that are available.

The national government is responsible for all roads classified as national roads, and provincial governments are responsible for provincial roads. In some provinces the provincial governments may engage the Department of Works (DoW) to undertake maintenance on their behalf. DoW has three major divisions or sections: Design and Major Contracts, Operations, and Corporate Services.

Data Collection

On the basis of a list of classified roads provided by DoW, the network was subdivided into geographical locations and assigned to survey teams. Each road section was listed on a survey form that provided the survey team with the road name, road number, length, and physical features (such as rivers or other permanent landmarks) for starting and ending sectional surveys. Road sections had a planned length, typically ranging between 5 and 15 km.

In the field, the survey teams liaised with DoW provincial staff to revise the survey forms to take into account any recent developments and changes. The equipment was set up and calibrated, the survey was mobilized, and computer file numbers and other relevant information were recorded on the forms. These survey forms were later used in the office to cross-reference and quality check input data.

Two procedures were used for data collection. The preferred and by far the quickest procedure was to use vehicle-mounted Roadmaster equipment. Surveys were accomplished at a speed of 20 to 70 km/h, and data were directly input into the onboard computer. In some locations, due to inaccessibility (bridge washouts, poor road conditions) or simply because of remoteness and the difficulty of securing a survey vehicle, a manual method was used. The manual method collected the same data as the Roadmaster but used handheld Global Positioning System (GPS) equipment and visual roughness and surface condition measurements. Results were tabulated manually for later transfer into the road condition database (RCDB). The same survey form was used in both methods.

The Roadmaster survey equipment consisted of the following components: central unit, roughness sensor, odometer, GPS receiver, road-condition coding keyboard, laptop PC, and connecting cables. The equipment was transported to survey locations by air, installed on four-wheel-drive vehicles, and calibrated. Installation and calibration took approximately 1 day at each location. Survey data were stored on diskettes and sent regularly to the head office for postprocessing. Postprocessing of survey data consisted of editing, analysis, and transformation of the coordinate system.

All survey data collected by the project included GPS data that were recorded on location at 1-s intervals and provide accuracy within a range of 50 m.

The project used two types of GPS equipment. The first type is a GPS receiver that is integrated into the Roadmaster survey equipment mounted on survey vehicles. The second type is a handheld unit that is used to collect location data on small, isolated networks and remote locations and to carry out any supplementary surveys. This approach ensures that important roads are surveyed at a steady pace with minimum delay due to transporting and setting up equipment at new locations.

To aid the survey teams in standardizing survey procedures and maintaining quality control, a series of checklists was developed. These checklists covered equipment, daily diaries, and performance monitoring.

RAMS adopted the road-numbering convention used by DoW, which is well understood throughout the country.

The start and end of each section are visually recoverable and were fixed by coordinates and distances from known points. In addition to location data (coordinates) and length of each road section, data relating to surface condition parameters also were collected. The measurement of surface condition varied depending on whether the surface was sealed, gravel, or earth.

The surveys were carried out using two sets of Roadmaster road-condition survey equipment and measured the surface roughness and recorded the condition of the road. The equipment can be used on both sealed and gravel roads and also records distance data and GPS coordinates.

The Roadmaster apparatus contains the following components:

- Central unit (300 × 400 × 120 mm, plus connectors);
- Accelerometer (approximately 4 × 4 × 1 cm);

- Pulse detector connected to the speedometer cable;
- Keypad connected to the central unit;
- Power supply connection, 12 V (cigarette lighter connection); and
- Notebook PC (Compaq Armada 1572, P2330, 16 megabytes RAM, Windows 95 English).

Survey data were postprocessed in two stages. The first stage was carried out by the survey team and consisted of checking that road link numbers, numbers of sections, and lengths of sections were correct; that roughness values were within an acceptable range; that surface type was correct; and that GPS readings were logical. The survey team also recorded any special events that may have affected the results in a survey diary.

The second stage of postprocessing was carried out at DoW headquarters and consisted of verifying the consistency of all survey data files, automatic checking for possible duplication of sections, automatic opening of the Access "form," and updating of the section file.

Surveys of approximately 6093 km (82 percent) of national roads and 874 km of national institutional roads were completed by the end of September and covered all provinces. Throughout the 19 provinces, some 1303 km could not be surveyed because of access restrictions resulting from

- The road's isolated location on an island or inland;
- Poor road conditions or inclement weather;
- Security risk in the area; or
- Prohibited access because of impassable river crossings, landslides, or overgrowth through lack of use.

A summary of the lengths of classes of road in the network is shown in Table 2.

RAMS Components

A road asset management system is one of the most important tools a road authority should have in order to efficiently manage a nation's road network. Establishing an asset management system generally takes years and involves tasks that are often carried out by different units in an organization. Combining these tasks under a common asset management umbrella helps improve planning and decision making and efficient use of funds. When several systems are interconnected under a common umbrella, further improvements in compatibility and exchange of data among different parts of the system are also encouraged.

RAMS has been established using as much data from existing data banks as possible. DoW already has valuable information on the physical characteristics of roads and bridges, traffic volumes, road conditions, costs, and geographic location. This information was collected during previous studies and updated by regular data collection efforts. In addition to using existing data, the project carried out a comprehensive road condition survey that systematically collected geographic location and road condition data. The survey covered all national roads.

To successfully establish RAMS within the given time frame, the system has been designed with the precondition that all major software elements are standard off-the-shelf programs, and together they will form a package suitable for road asset management. The package contains all elements needed for operating data banks, planning maintenance activities, performing economic evaluation of projects, and reporting to decision makers.

RAMS (see Figure 3) runs on PCs connected to the DoW's local area network. Copies of all data have been saved on CD-ROMs and eventually will be saved on drives under the responsibility of the Information Technology Branch. This will ensure that important data are always saved as backup copies and that permitted outside users have access to all data.

RAMS uses a selection of popular off-the-shelf software as the basis of the system to ensure that program development and upgrades do not form a constraint to RAMS's sustainability. This also ensures that future user support on technical issues is available from a number of sources.

Microsoft Access is used for managing the road condition database, with some procedures being carried out under Excel. The RCDB established by RAMS contains data from existing data banks as well as the results from comprehensive and systematic surveys of all accessible national roads. Because surveys include the collection of GPS data, RAMS also provides updated maps of the road network. The RCDB links information from various sources and stores it into road sections, which are relatively homogenous stretches of road with a length

TABLE 2 Summary of Road Lengths by Class (Papua New Guinea)

Surface Condition	NR	NM	ND	TOTAL	NI
Sealed	1391	452	210	2053	164
Gravel	1716	1574	2053	5343	1074
TOTAL	3107	2026	2263	7396	1238

NOTE: Values given are in kilometers.

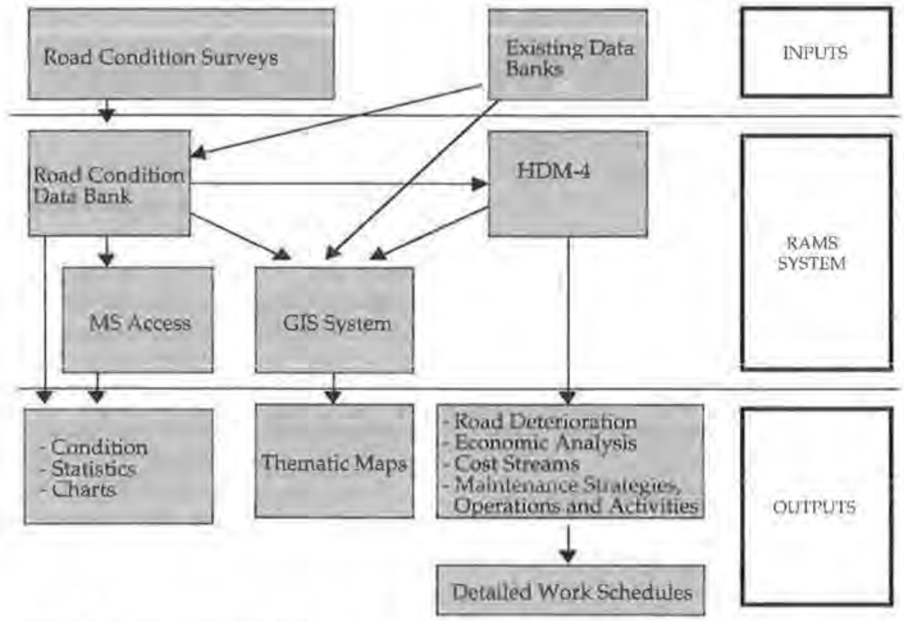


FIGURE 3 Diagram of RAMS.

generally varying between 5 and 15 km. The RCDB also contains information on maintenance standards and built-in automatic procedures for producing standard reports.

HDM-4 is used to evaluate alternative maintenance strategies and to carry out economic analysis to prioritize major development projects. Maintenance funds are severely limited in Papua New Guinea, and therefore maintenance planning must be carried out under a constrained budget. Program level analysis and planning with a constrained budget had not yet been carried out at the time this presentation was written. The RCDB has been developed to automatically provide HDM-4 input files on any or all road sections. The project has used beta versions of HDM-4 to ensure that data compiled by the project are compatible with data input requirements of HDM-4.

The role of HDM-4 applications is summarized in Table 3.

RAMS also includes a geographic information system (GIS) application that produces thematic maps based on GPS data collected during road condition surveys. The GIS system is used to illustrate RCDB data and to provide a practical means of presenting information to decision makers. After careful consideration, the consultant selected ArcView (including ArcExplorer) as the GIS software for RAMS. ArcView Desktop GIS is a common platform for thematic mapping, and ArcExplorer is a GIS application for occasional users and a platform for querying, reviewing, and displaying data.

Maintenance Planning

Road Network Classification

The project prepared initial classification criteria for reclassifying national roads based on their functional role. This classification serves as the basis for defining maintenance standards for each road section and assists in planning required maintenance operations. The classification is based on traffic volumes and existing administrative categories and therefore, in addition to indicating the

TABLE 3 Summary of the Role of HDM-4 Applications

Activity	Time Horizon	Responsible Staff	Spatial Coverage	HDM-4 Tool
Planning	Long term (strategic)	Senior management and policy makers	Network-wide	Strategy analysis
Programming	Medium term (tactical)	Middle level professionals	Sub-network	Program analysis
Preparation	Budget year	Technical staff	Project level	Project analysis

functional class (FC) of roads, also provides a basis for defining maintenance classes for roads. Unlike previous maintenance prediction systems used by DoW, RAMS prioritizes maintenance activities depending on the importance of the road. For this purpose, roads have been reclassified by functional class, depending on the volume of traffic they carry.

To further assist in prioritizing maintenance activities and setting appropriate maintenance standards, each road section has been assigned a maintenance standard (MS) on the basis of its functional class and pavement type as shown in Table 4.

Maintenance Operations

The network is typically in a very deteriorated state. For some years the level of budget support has been sufficient only to keep the road network open, regardless of deteriorating surface conditions. With reduced funding levels, the managerial and technical resources and capability of DoW have been allowed to deteriorate to such an extent that DoW now has difficulty spending the limited funds that are available.

Even with full recognition of the importance of road maintenance funding, it is likely to take DoW 2 to 3 years to put in place an effective restructuring of the Maintenance Section and restoration of the managerial and technical resources and capabilities necessary to implement rehabilitation of the network.

Restoration of the whole road network to a "reasonable" condition will take time, maybe another 10 years. To allow for the progressive improvement of the network and to allow DoW to strengthen its capability in managing and implementing maintenance tasks, the maintenance plan should not be overly ambitious. Maintenance thresholds initially should be selected to ensure that the plan is fundable and can be implemented with the resources available. The following condition ratings have been selected based on a statistical analysis of the condition of the road network. In turn, these will yield intervention thresholds that will provide for rehabilitating the network at the rate of 30 million to 80 million kina per year over the next 5 to 6 years (additional to normal routine and periodic maintenance activities).

TABLE 4 Maintenance Standards Based on Functional Class and Pavement Type

Functional Class	Sealed Road	Gravel Road	Earth Road
FC1	MS1		
FC2	MS2		
FC3	MS2		
FC4	MS3	MG1	
FC5	MS3	MG2	ME1
FC6	MS4	MG3	ME2

Based on a statistical analysis of the network, the following intervention criteria and corresponding maintenance activities have been adopted by RAMS.

The specific maintenance activities used by RAMS are

- Sealing cracks and potholes,
- Edge and shoulder repairs,
- Overlay,
- Regraveling (resulting from bad conditions), and
- Culvert maintenance (small).

These activities are not subject to set frequencies or cycles and can be implemented by DoW provincial staff using simple planning procedures.

The major reconstruction activities used by RAMS are the following:

- Upgrading earth road to gravel road,
- Pavement reconstruction (single bituminous surface treatment 19 mm and double bituminous surface treatment 19 mm + 13 mm);
- Upgrading gravel road to sealed road (19-mm aggregate with no base and 19-mm with base);
- Earth road construction; and
- Sealed road construction (widths of 4.5 m, 5.5 m, 6.5 m, and 7.5 m).

These activities are not subject to set frequencies or cycles and can be implemented only after detailed planning and feasibility analysis.

The specified maintenance operations will be reviewed in May through July 2000 and may change significantly.

Training

Training within the project has focused on on-the-job training and formal training courses and seminars. Because staff in various organizations will use RAMS, training has been targeted at various levels in several government departments and provincial staff.

For RAMS operation and computer skills, training has concentrated on local counterpart staff who in turn will themselves act as trainers. To secure sustainability, it has been imperative that the counterpart staff be highly motivated and develop a responsibility for local ownership of the system. The counterpart staff also has been trained in road inventory and condition survey activities. Through these activities, the basic data for the management system are collected, and it is important that the staff running the system can judge the reliability of the information they collect. Training in road maintenance activities and principles also forms part of the training program.

Staff members from provincial DoW offices and the provincial administrations have participated in the actual road inventory and condition survey fieldwork. An ongoing training program in inventory and condition data collection has also been tailored to field personnel.

DoW, OoT, and ONPI staff have gained a better appreciation of modern management techniques related to roads and a clear understanding of the concepts involved as well as the benefits of adopting a more systematic approach to road management. A series of training workshops aimed at a broader DoW and ONPI participation has been organized.

Conclusions

The following conclusions were made during this first implementation of HDM-4 in Russia and Papua New Guinea.

- Time needed for implementation of a system should not be underestimated. Learning of any new topic will take time, and this requires a long enough project period.
- Use of a pilot version of any software in a real project is always risky. This project used a piece of software that was in its development stage. This evidently caused much delay and rerunning of analysis. However, valuable information for the future development of HDM-4 was gained.
- The need for personal contacts with local experts during the project is high. This project was run mainly from the central office in St. Petersburg. However, a more efficient, although more expensive, way of implementation would have involved more traveling to the subjects, in order to meet and discuss with the local experts closer to their own circumstances.
- The need for translation of the system to the local language was proved.
- Minimum calibration can be done everywhere, but a proper calibration of HDM-4 needs more time and more reliable local history, traffic, and condition data.
- The practical results of this project (i.e., HRMP) were applicable, but the interpretation of results has to be done very carefully. It should be noted that the first results can always incorporate errors, but those errors cannot be found without trial-and-error procedures.

Acknowledgments

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Improvements in Highway Maintenance Management in Greece

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The main features of a computerized system to provide decision support to the agencies involved in highway maintenance management in Greece are presented. Development of the system focuses initially on pavement management, with other highway elements (e.g., side slopes, bridges) to be considered at a later stage. The system includes a database and modules for pavement performance prediction, resource allocation, and project management. In addition, a user interface system with appropriately designed input/output forms and GIS data representation improves applicability. The major pavement defects are cracking (mostly alligator type, longitudinal, and transverse), potholes, corrugations and rutting, bleeding, raveling, and polished aggregate, which results in high roughness and low skid resistance. These defects are represented in the system by four parameters: cracking index, index to the first cracking, roughness index, and skid resistance index. Further, a number of possible treatments have been identified and described in terms of materials, methods, machinery, and cost requirements. For each defect, all feasible treatments are considered, and the best maintenance strategy is produced considering relative costs, funding availability, and maintenance needs over time within the network.

Pavement management systems (PMSs) have been used since 1970 to provide decision support in the management process, but many agencies in various countries still do not use them in their management activities (*1*). A difficulty in implementing a PMS is that, as a result of particular oddities that are encountered in each agency, the transfer and implementation of an existing PMS may not be feasible and always must consider the local conditions. In addition, lack of historical data and models to predict pavement performance under local conditions leads to requirements of increased time and effort to set up a new PMS.

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In a recent survey in 60 agencies in the United States and Canada, the most common parameters for pavement condition assessment (and data collected in the corresponding PMSs) are surface distresses, roughness, friction, and structural capacity (*2*). Pavement condition performance is being expressed with combinations of indices derived from the above data types. To name a few, the PMS of Arizona initially had included four parameters: cracking, index to the first cracking, change in the amount of cracking during the previous year, and roughness. Because of the large number of condition states produced by this classification, "cracking during the previous year" was omitted later to make the analysis more flexible (*3*). Skid resistance data were collected but not regarded as a major input into the PMS whereas deflection data were collected for pavement design (*4*). In North Dakota, three indicators were developed for pavement performance assessment: an overall distress index, a structural index, and a roughness index (*5*). In South Dakota, pavement performance curves were developed using individual indices (fatigue cracking index, transverse cracking index, rut depth index, and ride index), and a composite index was used to describe the overall pavement (*6*).

Pavement management systems developed in Europe include various combinations of indices. In Finland, the system considers bearing capacity, pavement defects (alligator cracking, longitudinal cracking, and patching), rutting, and roughness (*7, 8*). In Germany, data are collected for longitudinal and transverse unevenness, skid resistance, and surface damage (cracking, raveling, and patching) (*9*). In Denmark, the system considers longitudinal unevenness, skid resistance, and rutting (*10*). In Hungary, pavement condition is evaluated in terms of structural capacity, unevenness, pavement surface quality, rut depth, and drainage condition (*11*). In Spain two indices are used: a structural index (resulting from fatigue distresses) and a friction index (*12*).

An important element with direct consequences on PMS effectiveness is the procedure used for predicting future pavement condition. Prediction is generally performed via the following methods:

- With relationships transferred from other applications,
- With relationships derived from existing data,
- With probabilistic methods based on existing data, or
- By using expert opinion.

Deterministic relationships have been developed and reported in the literature based on long-term data collection in various countries (*13*). Direct transferring among applications allows immediate implementation; however, results may not be effectively transferred from one region to another. In addition, there is limited flexibility to include desirable parameters that are different from or additional to the ones provided in the model. The second method requires the existence of data within an appropriate time span to realistically describe pavement performance in time. Probabilistic methods are typically based on Markov analysis with historical data (*7, 14–17*). Pavement condition prediction based on expert opinion has been used in applications when no historical data are available (*6, 18*).

Maintenance actions can be categorized as follows (*13*):

- Routine maintenance (local repair of pavement and shoulder defects, drainage, side slopes, traffic control devices, snow and ice control, cleansing, and safety);
- Resurfacing (full-width resurfacing of the pavement to preserve surface characteristics and structural integrity); and
- Rehabilitation (full-width and -length surfacing with selective strengthening and shape correction to restore structural integrity or ride quality).

Maintenance management in Greece has been applied empirically in the past without computerized decision support systems. As a result, maintenance decisions have a short (1-year) planning horizon. The only noticeable effort toward the development of a PMS is reported by Nikolaidis and Evagelidis (*19*). In this program, pavement performance prediction is based on World Bank prediction models (*13*) and includes the following parameters:

- Cracking initiation and progression in new asphalt concrete pavements, asphalt overlays, or slurry seal;
- Raveling initiation in slurry seal surfaces; and
- Skid resistance in new pavements.

The overall pavement condition is described by a composite index of 17 distresses. Each distress is classified according to its importance, severity, and extent of appearance. Simplified rules for maintenance decisions are based on preset thresholds related to the extent of appearance of the main distresses. If a specific threshold is exceeded, a decision for appropriate action is made. Otherwise, only routine maintenance is applied.

A new maintenance management system is being developed for application in the highway network of Greece. It is expected to provide decision support to maintenance agencies for planning, budgeting, scheduling, and performing maintenance actions in order to keep the road network at or above the desired level of performance. Management will include all maintenance aspects (pavements, side slopes, bridges, etc.). At this stage, however, the focus is on pavement management. With respect to side slopes, the stability of cuts and embankments will be considered, prediction of possible failure will be attempted, and preventive maintenance actions will be sought. The main steps of the work are

- Analysis of user requirements and investigation of pavement defects and maintenance practice,
- Model development for assessing pavement behavior through time,
- Development of a methodology for resource allocation and management, and
- Computer implementation and field application.

The system includes a database in which all input and output information is stored and a user interface module with geographic information system (GIS) representation capabilities. Data collection and analysis issues are also discussed in this paper.

In recent years, large-scale reconstruction, upgrading, or new construction of high-speed roads is under way in Greece. The need to keep the road network in an acceptable performance level makes the application of computerized maintenance management more imperative than before. In addition, new highways can provide an ideal field laboratory for testing, evaluating the effectiveness, and enhancing each element of the system.

STRUCTURE OF THE PROPOSED MANAGEMENT SYSTEM

The proposed architecture of the system is illustrated in a simplified form in Figure 1. The heart of the system is the database where all necessary information (input and output) is stored. Three modules are used to produce the

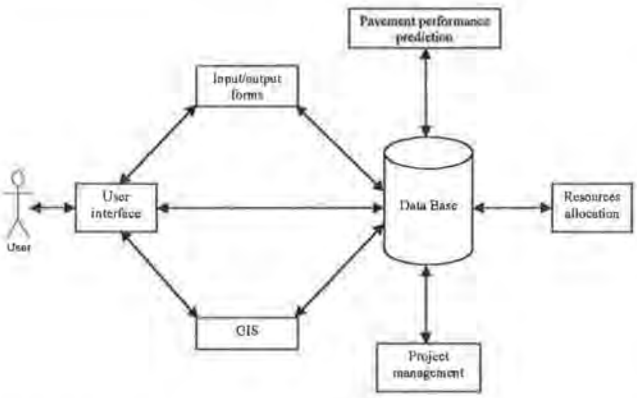

FIGURE 1 Proposed system architecture.

best maintenance strategy over the network and within the planning horizon:

- A module for predicting pavement condition over time based on the current condition and other parameters;
- A module for optimizing the allocation of the maintenance budget to road sections according to maintenance needs, desired pavement condition, and budget allowance; and
- A module for organizing and executing the maintenance projects.

The system is supplemented by elements that facilitate user interface. Such elements include forms for inputting data and viewing results and information representation through GIS. Individual system elements are described in more detail below. System development has followed through investigation of the procedures that are currently used for highway maintenance and the user requirements toward the development of an improved management system. In particular, a questionnaire was developed and filled in through successive interviews with two agencies responsible for highway maintenance at corresponding districts. The main subjects of the query concerned highway characteristics, maintenance practices, budget allocation procedures, maintenance actions and costs, and expected desirable features of a computerized decision support system.

Database

A database has been developed to store the necessary data for maintenance management. It has been implemented in the SQL Server database management system. Information to be stored in the database includes the following.

- General data—highway number and identification, class (primary, secondary, or tertiary), length, and location;
- Geometry data—highway section and length, design characteristics (width, number of lanes, shoulder type and width, grade, and curvature);
- Pavement design data—pavement type, materials and thickness of layers, material properties [e.g., subgrade California bearing ratio (CBR), asphalt content, and Marshall stability of asphalt concrete layers];
- Traffic data—traffic volumes expressed as average annual daily traffic (AADT) and axle loads expressed as 18-kip equivalent single-axle loads;
- Pavement condition data—surface distresses (e.g., cracking, rutting, potholes), roughness, deflection, skid resistance, and so on;
- Maintenance procedures—main types of maintenance actions, and material and resources requirements;
- Historical data—construction data, pavement condition, maintenance actions, traffic data, and accident data;
- Cost data—pavement construction cost, maintenance, rehabilitation, and reconstruction cost; and
- Environmental data—climatic conditions (e.g., temperature, rainfall, and snowfall).

Pavement Performance Module

The proposed methodology for pavement condition prediction is based on Markov analysis. Probabilities for the transition matrices will be established through an expert opinion procedure. This is deemed to be the best approach because no historical information on pavement deterioration exists. The main advantages of the expert opinion method are that (*a*) it allows immediate application with limited effort and without need of long-term data, (*b*) it provides results in any form compatible with the prediction method, and (*c*) it allows updating when field data become available. Among the disadvantages of the method are the reduced accuracy in evaluation, subjectivity in rating, and difficulties in assessing deterioration individually for each defect. The prediction procedure will be evaluated (to the degree possible) in terms of result agreement with widely accepted relationships derived from other PMSs. Transition probabilities may be updated later (when actual data are available) on the basis of a Bayes decision rule analysis.

Resource Allocation Module

The system uses four indicators to access pavement condition as described previously. Further, a number of possible treatments along with the corresponding costs have been determined. For each defect, all feasible treatments are considered, and the best maintenance strategy is produced considering relative costs, funding availability, and maintenance needs. Optimization of maintenance budget allocation is performed through a linear programming model in which the objective function aims to minimize the total maintenance cost over all highway segments and the planning horizon. At this stage, the objective function does not include a user-cost element because this research effort focuses mainly on optimal budget allocation to maintenance works and because there has been no reliable user-cost assessment in the country to date. The constraints are set to maintain the road condition at a desirable level. Targeted condition levels may vary across network branches according to the importance of the branch, traffic loads, and environmental conditions that affect the deterioration rate. The user has to evaluate alternative scenarios with respect to condition levels to conform to the available budget. In addition, the system will provide a tool to maintenance agencies to justify demands for higher outlay from state funds.

Project Management Module

This module aims to provide decision support for the execution of maintenance works. In particular, maintenance actions at separate highway sections are grouped (according to the position of the section and the resemblance of actions in terms of resource requirements) to form projects of desirable size. For each project, the system establishes work schedules and assigns physical resources based on priority rules and resource availability constraints. Maintenance priority is given according to defect type and influence on safety (e.g., slipperiness), extent or severity of defects, traffic loads of the particular section, and environmental conditions. In addition, a monitoring system is being developed to assist supervising authorities to better control maintenance projects and subcontractor work and also to enhance the entire maintenance management at the network level by collecting, recording, and feeding information about performance, cost, and time back to the system.

User Interface

User interface provides access to the system components and allows prompt interaction among the digital map that is used for graphical data representation, the input-output forms, and the database. The user can insert information to the database; retrieve, view, and modify existing data; compose and run management scenarios; choose the type of result representation, and so on.

Input/Output Forms

Data input is done through appropriate forms with windows and tables that have been designed to allow even personnel with little computer experience to run the system. Similar forms have been designed for presenting the results of a run. Desirable parameters can be presented in many convenient forms. For example, pavement condition can be viewed by road sections, time, or type of distress.

GIS Representation

A digital map has been implemented through GIS software. The network is digitized at 1000-m sections. Figure 2 illustrates a typical view of the pavement condition on a part of the network. Data that will be presented in a digital map include the following:

- Geography (cities, type of land terrain);
- Road geometry characteristics (identification, length, number of lanes);
- Pavement characteristics (pavement type, layer characteristics);
- Traffic loads (vehicle counts and composition);
- Pavement condition at a given time (type and extent of distresses);
- Proposed maintenance actions including costs and time requirements; and
- Network classification (primary, secondary) and desired condition levels.

The work flow and system operations are summarized as follows:

1. The user chooses to create a new scenario or to retrieve an already saved scenario through the user interface.
2. Then, appropriate data are inserted or retrieved from the database to form a new scenario. These data include the desirable part of the network, current pavement condition, and desirable condition level at future periods. New data are inserted through the input forms.
3. In the next stage, the user can view the current pavement condition on the GIS map.
4. The user activates the Pavement Performance Module to assess the pavement condition in each of the following periods within the planning horizon. The results of the process appear, if desired, by the GIS representation and are saved to the database. The user also can intervene manually and modify these results if they are considered unrealistic.
5. The user activates the Resource Allocation Module, which determines which maintenance action is best and when to apply it for any road segment and type of distress within the study period. The result corresponds to the minimum required budget for retaining the network at a desirable condition level. If the available budget is not sufficient to cover the cost of all maintenance needs, the user should lower the expected condition level or assign variable condition levels and repeat the analysis.

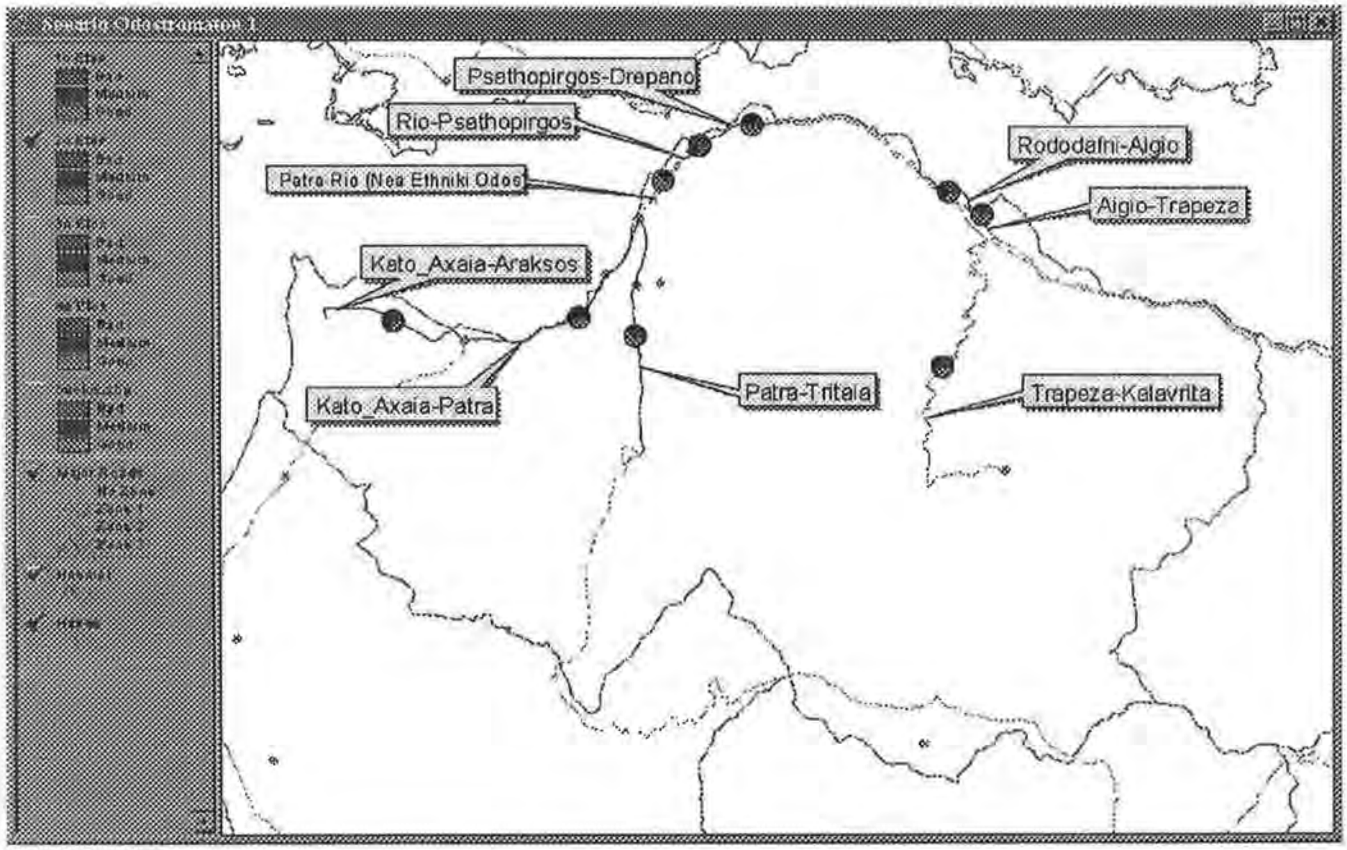

FIGURE 2 Pavement scenario of Achaia district highway network.

6. For the selected scenario, information will be released regarding the type and extent of pavement defects through time, type, and timing of proposed maintenance actions. The existence of defects will be verified by field inspection. Using all this information, the Project Management Module will be used to allocate physical resources to maintenance projects.

7. A monitoring system will collect and record relevant information and provide feedback for all aspects of the management process (e.g., pavement condition deterioration, maintenance cost and time, and resource productivity). This information will significantly improve the decision process, which now is developed based only on rough estimations.

Current Maintenance Practice in Greece

The highway network in Greece measures about 9500 km of roads, of which 27 percent are classified as primary (multilane highway serving high traffic volumes), 56 percent as secondary (two-lane highways), and 17 percent tertiary (local low-volume roads). In almost the entire network, road pavements are of the flexible type. The asphalt concrete used for pavement construction complies with Greek Standard Specifications, which have been set since 1966 [STS, A-265 (*20*)]. Besides traffic loads, another factor that results in pavement disintegration is temperature variation through time. High ambient temperatures (35°C to 40°C) are observed in the country during summer. Low temperatures and freeze-thaw cycles in winter, due to the mountainous nature of a large part of the country, lead to increased pavement deterioration rates and, particularly, deformation, loss of coarse aggregates, edge cracking, and so on. The major pavement defects observed in the roads are cracking (mostly alligator type, longitudinal, and transverse), potholes, corrugations and rutting, bleeding, raveling, and polished aggregate, which results in high roughness and slipperiness. Design specifications from previous decades do not adequately deal with skid resistance. As a result, road slipperiness is a major problem on the highway network, with safety consequences. Friction courses recently have been applied extensively but do not cover a large part of the highway network yet. The above pavement defects are mainly due to the following factors: (*a*) pavements are aged in considerable parts of the network; (*b*) pavement design is unable to accommodate rapidly increasing traffic loads; (*c*) construction has not always met specifications (in terms of structural capacity, materials, and construction methods); and (*d*) maintenance has been inadequate due to limited funding.

Maintenance management is conducted at the district level by Regional Highway Management Administrations (RHMAs), which are state agencies supervised by the Regional Council for political matters and decisions and by the Ministry of Public Works for technical support and funding provision (Figure 3). An RHMA supervises maintenance projects assigned to subcontractors and performs quality control for supplied materials. Further, the agency collaborates with external consultants for additional inspections and material tests.

Highway infrastructure generally contains the following elements:

- Pavement maintenance,
- Side slope maintenance,
- Bridge maintenance,
- Winter maintenance,
- Highway lighting maintenance,
- Traffic signal maintenance,
- Highway cleansing,
- Highway drainage, and
- Grass cutting and tree pruning.

Pavement maintenance activities in RHMA can be classified in four categories: routine maintenance, preventive maintenance, corrective maintenance and rehabilitation, and reconstruction.

- Routine maintenance—includes surface defect repair (pothole patching, crack filling, and so on); pavement surface cleaning; drainage maintenance (side drains, culverts); grass cutting, hedge cutting, and tree pruning; replacement of traffic barriers, traffic signs, and other highway furniture; and winter maintenance (snow removal).
- Preventive maintenance—rarely performed due to limited available funds (funding is allocated primarily to routine and corrective maintenance and rehabilitation). It involves crack filling, pothole patching, and slurry seal in order to improve surface skid resistance.

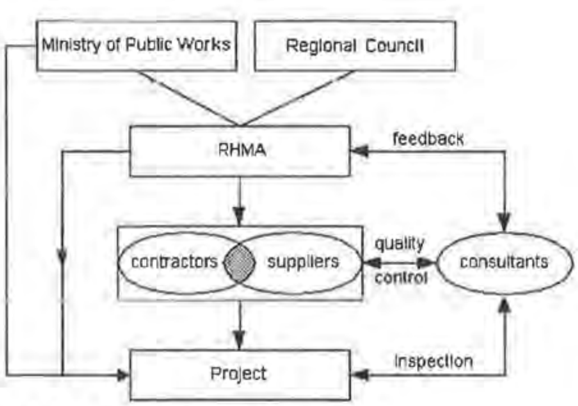

FIGURE 3 RHMA project organization.

- Corrective maintenance and rehabilitation—the main type of pavement maintenance. Involves asphalt concrete overlays (at various thickness levels) with all the necessary prerequisite work.
- Reconstruction—applied when severe distresses repeatedly appear in a highway section; reaches any pavement layer as necessary.

New technologies, materials, and techniques are currently introduced to improve maintenance performance/cost ratios. Such treatments include stone mastic asphalt courses, surface dressing, rubber asphalt, and pavement recycling. Routine maintenance is performed through RHMA's own resources (personnel and machinery) whereas large-scale rehabilitation is assigned to subcontractors. Pavement condition is monitored frequently, and inspection results are recorded. If the observed distress level is considered high enough to create hazardous conditions for travelers, prompt maintenance is applied; otherwise, maintenance is scheduled according to the yearly program.

PAVEMENT CONDITION ASSESSMENT AND MAINTENANCE ACTIONS

Pavement distresses that are taken into account (directly or indirectly) for pavement performance assessment in the system can be grouped in four main categories: cracking, deformation, disintegration, and friction (as shown in Table 1).

Pavement performance is described by four indices and corresponding levels as follows:

- Cracking index (3 levels),
- Index to the first cracking (3 levels),
- Roughness index (3 levels), and
- Skid resistance index (2 levels).

The ranges of the first three indices are shown in Table 2. Cracking index involves 5 main cracking types: alligator, longitudinal, transverse, slippage, and edge cracking. Index values range from 0 to 100; 0 is the best condition with no cracking and 100 the worst. Roughness is expressed with the international roughness index (IRI).

TABLE 1 Pavement Distresses Considered in the System

Cracking	Deformation	Disintegration
Alligator cracking	Local depressions	Potholes
Longitudinal cracking	Local upheaval	Raveling
Transverse cracking	Corrugations	
Shrinkage cracking	Rutting	**Friction**
Edge cracking	Lane-to-Shoulder Drop-off	Polished aggregate
Reflection cracking	Patching	Bleeding
Lane and widening cracking		
Slippage cracking		

TABLE 2 Ranges for Three Pavement Performance Indices

Level	Cracking	Index to First Cracking (years)	Roughness IRI, m/km
Good	< 25	> 13	< 2
Medium	25-50	5-13	2-4
Bad	> 50	< 5	> 4

Skid resistance index is expressed at the present phase with two levels: good–medium ($SN_{40} > 30$) and bad ($SN_{40} < 30$), where SN_{40} is the skid number measured with the ASTM skid trailer. Skid resistance has not been used extensively as a condition parameter in other pavement management systems but is an important indicator here due to slipperiness problems. Existing aged pavements that were constructed with limestone aggregates (and account for a large part of the highway network) result in SN_{40} values between 19 and 25. In newly constructed pavements the range is between 27 and 28. Newly constructed friction courses (porous pavements, slurry seal, and so on) yield higher skid resistance values (SN_{40}: 45–60). Pavement slipperiness reflects a main criterion for treatment selection. It is noted that almost any treatment improves pavement skid resistance (to a certain degree) even if the action aims to cure problems resulting from other defect types.

The highway network is divided in categories according to road class (primary, secondary, and tertiary); traffic volumes (high, medium–low); and terrain type/environmental conditions (low altitude, mountainous), forming eight categories. Each category can be treated differently than others in many aspects—for example, desired condition levels, pavement deterioration probabilities, type of maintenance actions, maintenance priority, funding constraints, and so on.

Evaluation of pavement performance requires systematic data collection of all parameters that reflect pavement condition. A PMS becomes more effective if, besides manual observations, additional objective data are collected through mechanical equipment. One of the objectives of this project is to organize a process for continuous collection of pavement condition data. In this respect, both manual and equipment-based measurements have been initiated on a network section as part of a pilot application. RHMA personnel inspect pavement and record data concerning cracks, rutting, and potholes in appropriately designed forms. In addition, video recording will be used to assess pavement condition deterioration over extensive highway sections through time. Further, mechanical equipment is used to gather data on certain parameters—for example:

- Longitudinal evenness (pump integrator, 3-m beam);
- Transverse evenness, rutting (3-m beam);
- Skid resistance (ASTM skid trailer and portable skid resistance tester);
- Surface texture (laser texture meter); and
- Deflection measurement (Benkelman beam).

Structural capacity will be estimated from deflection measurements and destructive tests involving coring to provide pavement layer thickness and material properties.

With respect to maintenance actions, selection was based on current practice in Greece and in other highway maintenance programs. This procedure led to some 20 actions, which may lead to computational inefficiencies in system application. According to Wang et al. (*3*), the number of maintenance actions in Arizona's PMS was reduced from 17 to 6 to avoid similar problems. On the other hand, Saudi Arabia's PMS enabled as many as 20 feasible maintenance actions (*18*). In the present phase, the effect of treatment number on system application cannot be evaluated because network size and segmentation play an important role. To avoid inefficiencies, the number of alternative treatments has been reduced to 7, as shown in Table 3. An effective reduction is accomplished by classifying similar actions in groups, eliminating actions that are applied rarely or are not expected to be applied in the future. Routine maintenance at this stage is limited to surface defects and drainage maintenance.

Conclusions

The computerized decision support system that is being developed for highway maintenance management application in Greece includes the following main modules:

- A database in which all necessary information (network geometry, traffic loads, pavement condition, maintenance actions and costs, and so on) is stored;
- A module for pavement performance prediction through time based on Markov analysis;
- A module for optimal budget allocation according to maintenance needs;
- A module for management of maintenance projects, and
- A user interface with appropriate input/output forms and data representation on a digital map (GIS).

TABLE 3 Pavement Maintenance Actions

Routine maintenance
Seal coat
Overlay courses
Mill and replace
Reconstruction in primary network
Reconstruction in secondary network
Recycling

Pavement condition is represented in the system by four parameters: cracking index, index to first cracking, roughness, and skid resistance. For each defect, index levels have been set to differentiate among pavement condition states. Due to the lack of historical data on pavement performance and maintenance treatments, pavement condition prediction initially will be based on expert opinion. Further, a number of possible treatments have been identified and described in terms of materials, methods, resources, and cost requirements. They include routine maintenance, seal coat, overlay courses, mill and replace, pavement reconstruction and recycling. For each defect, all feasible treatments are considered, and the best maintenance strategy is produced considering relative costs, funding availability, and maintenance needs. Optimization is performed through a linear programming model that selects appropriate maintenance actions and time of application so as to minimize the total maintenance cost over the network and within the planning horizon. With respect to project management, individual maintenance activities are grouped to form projects of desirable size, and resources are allocated following priorities set according to safety considerations, traffic loads, and environmental conditions.

ACKNOWLEDGMENTS

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Total Maintenance Contracts

Joe S. Graff

The Texas Department of Transportation (TxDOT) began contracting maintenance in the mid-1970s with a few roadside mowing contracts. Contracting continued to increase through the 1980s with many activities contracted, such as picnic and rest area maintenance, guardrails, raised pavement marking, striping, and other mostly non-pavement-related activities. A dedicated program for preventive maintenance was created in 1986 with $145 million for contracted seal coats and light overlays. The Texas legislature emphasized the contracting of TxDOT's maintenance by attaching a rider to the department's appropriation bill in 1989, which required TxDOT to contract a minimum of 25 percent of routine maintenance if cost-effective. In 1991, the Texas legislature passed a bill that required TxDOT to increase maintenance contracting to 50 percent by 1996. This also was contingent on cost-effectiveness. It included routine and preventive maintenance. In July 1999, TxDOT let two total maintenance contracts. The philosophy of a total maintenance contract is totally different from that of a regular maintenance contract. It is more of a management contract whereby the contractor is required to maintain a prescribed level of service for a lump sum bid. The contractor has total control to determine what work to perform, what materials to use, methods, schedule, and so forth. The history and evolution of maintenance contracting in Texas and the letting and results to date of the total maintenance contract are discussed. The specification and the condition assessment process that is being performed in conjunction with the projects are also discussed.

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The Texas Department of Transportation (TxDOT) began contracting a part of roadside mowing operations in the mid-1970s. A reduction in force after most of the interstate highway construction was complete emphasized the need to contract to maintain the high level of service citizens of Texas had come to expect.

The first contracts were for mowing. It was thought that this would be a cost-effective activity to contract because it was a seasonal activity with most of the work being performed between April 15 and October 15. It also required a large investment in equipment and was very labor intensive.

By contracting mowing, the department could reduce the number of maintenance forces and reduce expensive equipment inventory. Also, it was believed that developing a contracting industry would be relatively easy because local farmers could use their tractors and mowers to do the work.

Contracts were originally small, usually two to four contracts per county. This allowed many different contractors to bid on the multitude of projects. This was very effective and resulted in good competition, low prices, and the development of many contractors. The department continues to contract over 90 percent of mowing and usually mows only in spot locations or when a contractor defaults.

Contracting continued to increase in the 1980s, with many activities contracted, such as picnic and rest area maintenance, guardrails, raised pavement marking, striping, and other mostly non-pavement-related activities.

A dedicated program for preventive maintenance was created in 1986 with $145 million for contracted seal coats and light overlays.

In the past few years almost every maintenance function has been contracted to some extent.

Legislative Direction

The Texas legislature emphasized the contracting of TxDOT's maintenance by attaching a rider to the department's appropriation bill in 1989. Rider 28 required TxDOT to contract a minimum of 25 percent of routine maintenance if cost-effective.

Although the department was already contracting almost 25 percent of its routine maintenance operations, the legislative interest emphasized the need to continue development of the maintenance contracting process.

In 1991, the Texas legislature passed a bill that required TxDOT to increase maintenance contracting to 50 percent by 1996. This also was contingent on cost-effectiveness. This legislation again emphasized the need for continued increases in the contract area. Even though the legislation allowed the inclusion of preventive maintenance contracts into the contracting percentage, the maintenance division had to establish contracting targets for each of the 25 districts to ensure the 50 percent requirement was met by 1996.

The department has continued to increase contracting and currently contracts about 55 percent of the total maintenance effort.

Total Maintenance Contract

For over 20 years TxDOT had contracted single maintenance activities. In the mid-1990s the Houston district let several large multi-item contracts. Most maintenance activities on specific roadways were performed in a single contract. Although these contracts were for most of the maintenance effort on a number of highways, they were bid item contracts, where TxDOT inspected each activity, measured pay quantities, and paid for the quantities of work performed. TxDOT continued to operate the highways and was responsible for responding to public inquiries, permitting, and so forth.

Several times in 1997 and 1998 TxDOT looked into the possibility of letting a total maintenance contract. It did not appear to be cost-effective and the idea was rejected. Finally, in late 1998, a decision was made by the Texas Transportation Commission to try a pilot project.

The philosophy of a total maintenance contract is totally different from that of a regular maintenance contract. It is more of a management contract whereby the contractor is required to maintain a prescribed level of service for a lump sum bid. The contractor in effect takes over operation of the highways and has authority to make all decisions about the maintenance and operation of the highway. Contractors determine what work to perform and what materials and methods to use. They plan and schedule work, subcontract for work, and have the authority to utilize experimental materials, file claims to collect for third party damages, and so forth.

Contract Development

In 1999, for the first time in its history, TxDOT awarded two contracts for the total maintenance and operation of two sections of the state's Interstate highways.

These two contracts involve an unprecedented level of risk for the department and for the contractor. First, two of the most heavily trafficked sections of Interstate highways in Texas are involved—193 km (120 mi) of IH-35 in the Waco District and 96.5 km (60 mi) of IH-20 in the Dallas District. Second, this is the first time this type of contract has been used by TxDOT and, to the author's knowledge, the first time it has been awarded by a low-bid process anywhere in the United States.

The total maintenance concept emerged from the annual Texas Quality Initiative conference held in Fort Worth in February 1998. A conference breakout session received an informational briefing of the newly initiated total maintenance program in Virginia. Although initial reaction within the department to this type of contract was very negative, fears have been calmed by communication, education, and the professionalism and competence of the contractor.

The development of the specifications was a genuine collaborative effort involving the department and a number of interested potential bidders. Both maintenance projects were formally "kicked off" with major partnering sessions where the principal partners, the interested communities, and other stakeholders were represented.

Measurement of Quality

Previous maintenance contracts used in Texas required the contractor to meet a certain quality of work by specifying the materials and methods that were to be used. The total-maintenance-and-operation concept is different in that the outcome is specified and the contractor is expected to maintain the project to that specified level of service.

Performance standards were developed that defined the minimum level of service acceptable. These performance standards are minimum performance and quality measures for every element of work normally performed in the maintenance and operation of an Interstate highway system. They include all aspects of routine and preventive maintenance on the pavements, bridges, roadsides, traffic operations, and traffic services. They also include incident response, hazardous materials cleanup, and emergency repairs. Contractors are responsible for coordination with local governmental entities and law enforcement. They are responsible for processing damage claims and reimbursement from federal agencies in the case of a disaster.

Although TxDOT established levels-of-service guidelines about 10 years ago, they were very generic and were not detailed enough to use as performance standards. Developing the performance standards was the most difficult part of the specification and involved the largest number of people.

The team decided it was critical to develop a method to compare the quality before and after. Because TxDOT had not previously measured maintenance condition, a system had to be developed to measure the existing and resulting level of service. The result was the development of the Texas Maintenance Assessment Program (TxMAP).

TxMAP involves measuring the level of service on maintenance elements in four maintenance components: pavement, bridges, traffic services, and roadside. Random 1.6-km (1-mi) sections are rated every 16 km (10 mi). Bridges are rated in a separate evaluation. Each element (for example, rutting, failures, striping, signing, mowing, litter) is rated at each location, on a scale of 5 to 1, where 5 is excellent—new or like new; 4 is good—no work needed; 3 is fair—minimum acceptable condition; 2 is poor—needs work; and 1 is failed. A 1 to 100 score is determined for each element by taking the actual score and dividing by the maximum. Each element is given a priority multiplier depending on its relative importance based on the following maintenance priorities: safety, protect the investment, user comfort, and esthetics. The elements are then combined by multiplying the element score by the priority rating, summing all the resulting scores in each component, and dividing by the maximum possible score. The result is a 1 to 100 score for each component. The components are combined to give an overall score. This process is very similar to that described in *NCHRP Web Document 8* (*1*).

TxDOT's administration was so impressed with the TxMAP assessment process that they requested an evaluation of the whole Interstate system. This evaluation was performed from July through October 1999 and will be repeated this year.

Although a formal evaluation of the total maintenance contract has not been done, no complaints have been made by the traveling public, local municipal entities, or law enforcement officers about the level of service provided by the contractor. Comments have been made by TxDOT employees, who were impressed with the innovations the contractor used.

Issues Addressed

Because this is a relatively new concept in contracting for highway maintenance, many risks were involved. The maintenance division was very careful to get all affected parties involved as soon as possible. Good, open communication was believed to be the key in calming the fears of departmental employees and contractors about this type of contract.

Another big concern was cost. Lack of competition could result in increased cost of getting the work performed or in a deterioration in the level of service provided to the public. TxDOT has used a combined effort of state forces and small maintenance contracts to effectively maintain the highways. Initially, the team thought a contractor for the total maintenance and operation of these facilities could not compete and that costs would increase substantially. This was proved not true, as the successful contractor bid lower than anticipated.

One of the department's most critical functions is to respond to emergencies. This may include repairing damaged highway facilities caused by accidents or natural disasters, removing debris or hazardous materials, or assisting law enforcement officials with traffic control after an incident. The team was extremely concerned about the ability of the contractor to perform in emergency situations. Special emphasis was placed on performance standards to ensure an acceptable response would be provided in this area.

Another big concern was the effect on the morale of TxDOT maintenance forces. TxDOT employees are very proud of the quality highway system they have constructed, maintained, and operated over the past 83 years. Many maintenance employees have long histories with the department that may date back to their parents or grandparents. They intimately know the highways in their sections, where they have bladed snow, patched potholes, picked up dead animals, and, most importantly, assisted stranded motorists or helped out in accidents. No employees were displaced and no offices were closed. Total contracting of all maintenance on the Interstate system in these districts allows existing employees to be used on non-Interstate highways in the counties involved.

The failure of the contractor to respond could also damage the good working relationship that exists between the department and local entities. Another possible risk is objections by the traveling public or property owners. Other concerns were the political pressure to perform more of this type of contract or just the opposite, objections from contracting organizations and small or minority contractors.

In fact, a number of concerns were expressed by the contracting community that they could not bid this type of project. Because there were no quantities of work, they thought the risk was too great and they did not know how to bid the project. In reality, the contractor has subcontracted much of the work to the same contractors.

Involvement of Industry

The initial consideration of this type of project was discussed at the Texas Quality Initiative Conference held in Ft. Worth Texas in February 1998. A large group of people including TxDOT maintenance and construction engineers, construction and maintenance contractors, and material suppliers discussed this type of approach to contracting maintenance.

A number of contracting entities solicited consideration of a total maintenance contract from the department's administration. After discussion of a total maintenance contract was begun in TxDOT, meetings were held and input was received from Infrastructure Corporation of America (ICA), Nashville, Tennessee; Virginia Maintenance System (VMS), Richmond, Virginia; PBS&J, Dallas, Texas; and Roy Jorgensen Associates, Buckeystown, Maryland.

In any contract, the specification(s) is the most important controlling document in the contract. A large number of people were involved in developing the specification for this project. This specification was different from any other TxDOT specification because it is based on performance instead of methods and materials. The districts letting the contracts, Dallas and Waco, were the most intimately involved in the performance standards in the contract. The TxDOT Maintenance Division took the lead and, once a draft was prepared, solicited review and input from the TxDOT Maintenance Specification Committee, interested contractors and consultants, TxDOT's Public Affairs Office, TxDOT's Internal Review Office, the Texas Associated General Contractors, the Texas Attorney General's Office, and FHWA.

Because this was a new type of project, another way the team got input from the stakeholders was to hold a prebid meeting. Notices were sent to all contractors on the TxDOT bidders list and it was advertised in the paper. The meeting room was filled with contractors, consultants, suppliers, local governmental officials, and TxDOT employees. There were a number of issues discussed with mixed opinion from the affected parties. Several contractors expressed their concern about the lack of bid items and their ability to prepare a reasonable bid. The specification and bid documents were thoroughly discussed and questions were answered.

A partnering meeting was held with the contractor for each contract. Involved in the partnering session were TxDOT employees, the contractor (VMS), and officials from a number of local cities. All the affected players met, discussed, and resolved issues before the projects began. An important part of the partnering meeting was establishment of the appropriate team members and the issue escalation process.

Specification Summary: Special Specification—Total Maintenance and Operation of Highways

Note: This is a summary of the specification used, not the complete specification.

1. Description. This item shall govern for the complete maintenance and operation of highways including all its existing appurtenances and future additions. This includes main-lane roadways, frontage roads, shoulders, ramps, intersections, roadsides, bridges, rest areas, picnic areas, traffic operations, and so forth.

2. General. It is the intent of this specification that the contractor shall relieve the state of all duties traditionally performed by the state in maintaining and operating the highways. It is anticipated that no change orders, except for contract extension, changes in governmental policy, or changes in state or federal statutes, will be executed during the course of this contract.

2.1. Department Standards. Unless otherwise approved by the engineer, work performed and materials used under this contract shall conform to the latest version of all department manuals, standards, specifications, statewide special specifications, policies and procedures, and their addendum.

2.2. Coordination. In performing work under this contract, the contractor shall ensure that proper coordination exists with cities, counties, state and local law enforcement, utilities, fire departments, and other state and federal agencies.

2.3. Purchasing from People with Disabilities. The contractor shall comply with the provisions of Chapter 122 of the Texas Human Resources Code that are placed on the department.

2.4. Existing Contracts. Several TxDOT contracts with community rehabilitation programs will be in effect at the beginning of this contract.

2.5. Reporting. The contractor is required to have a personal computer that is capable of connecting to the department's information systems and will report to the department the following information:

- Work accomplished: Using the department's construction and maintenance contract system, the contractor shall report to the department work accomplished and unit cost.
- Highway condition report: By 8:10 a.m. each workday and as changes occur, the contractor shall report weather conditions and any lane closures using the department's highway condition reporting system.
- Condition assessments: The contractor will be required to perform monthly condition assessments of all elements of the highway and rights-of-way. These assessments shall be reported to the department each month.
- Complaints/service requests: The contractor shall report no later than the 15th of each month, in a format approved by the department, information on any complaints or service requests received from the public, prop-

erty owners, cities, counties, legislators, and so forth from the previous month.

• Accidents/incidents: The contractor shall report, no later than the 15th of each month in a format approved by the department, information from the previous month on any accident or incident related to work being performed by the contractor.

• Agreements: The contractor shall provide the department with copies of all agreements between the contractor and counties, cities, municipalities, sheltered workshops, prisons, and so forth that are associated with the work on this contract.

2.6. Traffic Signals and Illumination. The contractor will provide maintenance and operations (including utility costs) of various traffic signals and illumination as outlined in the general notes and specification data sheet(s).

3. Materials. The contractor will furnish all materials necessary to complete this work. The contractor shall furnish the engineer with documentation indicating material compliance with department specifications unless otherwise approved by the engineer.

4. Equipment. The contractor shall be responsible for furnishing all equipment, tools, and machinery necessary for the proper prosecution of the work.

5. Scope of Work. Excluding only those items of work listed in Subarticle 5.1, it is the responsibility of the contractor to perform all work required to maintain and operate the highway and its appurtenances. The contractor should be aware that this work also includes items such as catastrophic repair, hazardous material cleanup, and disposal.

The contractor shall pursue claims against third parties for damage caused to the highway or its appurtenances. The contractor shall also prepare the documentation in the required format to apply for emergency relief funds (ER) from the FHWA in the event of a presidential disaster declaration. The funds acquired by the department as a result of these claims or ER projects shall be added to the contractor's monthly payment in the month the funds are received.

Funds to repair major damage caused by catastrophic events not reimbursed by FHWA or third parties will be added to the contractor's monthly payment after the work is completed. The damage shall be of the extent that it is above and beyond normal routine or preventive maintenance and shall be a minimum of $50,000.

5.1. Items Excluded from the Contract. The contractor will not be responsible for the following items only:

• Courtesy patrols;

• Traffic management devices (such as cameras, changeable message signs, automatic vehicle identification readers/antenna, amplifier cabinets, detectors including acoustic, vehicle imaging vehicle detection, microwave);

• Agreements such as utility permits, driveway permits, multiple use agreements, construction and maintenance agreements, and other similar agreements; and

• Logo signing.

5.2. Traffic Control Plans. The contractor must perform all work in conformance with the *Texas Manual on Uniform Traffic Control Devices for Streets and Highways* (2) and the barricade and construction standards.

5.4. Public Notification. The contractor shall furnish and install signs notifying the public that the highway is under private maintenance and operation. Any information provided to the press shall be routed through the department's public information officer in the district for release.

5.5. Performance Standards. Listed below are performance standards, which shall be used by the contractor to schedule work. The safety of the traveling public is of utmost importance and shall take priority over any other work. Safety-related work shall be scheduled as soon as possible.

Note: Because of space limitations, only the elements with a few example performance standards are listed.

Pavement maintenance

Asphalt surfaces (travel lanes and/or shoulders)

• No ruts > 1.27 cm (0.5 in.).
• No unsealed cracks > 0.635 cm (0.25 in.).
• Patching, even and <0.635 cm (0.25 in.) high or low.
• Ride should be smooth with no discernible dip or hump and have a score of 3.5 or above on the Mays meter.
• Potholes will be repaired immediately.
• Base failures shall be repaired immediately.
• No edge dropoff > 5.08 cm (2 in.) and > 15.24 m (50 ft) long.
• No flushing allowed.

Concrete pavement (travel lanes and/or shoulders)

Roadside maintenance

Bridge maintenance
- Overall bridge
- Railing
- Deck
- Superstructures
- Substructure
- Channels
- Embankments

Traffic operations

6. Contractor Performance. If in the opinion of the engineer the contractor is not performing work according to this contract, the department may take steps to have the work corrected. This may include the use of emergency contracts. The costs associated with these measures will be deducted from any payments due the contractor. In addition, liquidated damages in the amount of $5,000 per working day, during the work correction period, will be deducted from the amount due the contractor.

7. Termination. This is an experimental project. If both parties to the contract agree in writing to terminate the contract, the department shall prepare a termination agreement, and the contract shall end 30 days after the date of the last signature.

8. Measurement. This item will be measured by the lump sum, as the work progresses.

9. Payment. The work performed in accordance with this item and measured as provided under "Measurement" will be paid for in partial payments in accordance with the schedule, utilizing the unit price bid for total maintenance and operation of highways (Table 1). This price shall be full compensation for this work and for furnishing all labor, equipment, materials, fuel, tools, and incidentals necessary to complete the work for a 5-year period beginning on the date of the original work order.

Should a construction or reconstruction project(s) occur involving portions of highway covered by this contract, the contractor may be relieved of items of work covered by the construction contract along those portions of highway for the duration of the construction project. Monthly payments to the contractor will be reduced by an amount agreed upon by the department and the contractor.

Monthly payments shall be made by multiplying the lump sum bid by the payment schedule percentage and deducting any amounts as indicated under contractor performance.

10. Contract Extension. If agreed to in writing by both parties to the contract, the contract may be extended an additional 36 months in accordance with the payment schedule (Table 2). Either party to this contract may request a revised pay schedule for the contract extension and, if executed by change order, will replace the following.

Monthly payments shall be made by multiplying the original lump sum bid by the payment schedule percentage and deducting any amounts as indicated above under contractor performance.

TABLE 1 Contract Payment Schedule

Year		Monthly Payment Schedule (Percent)	Cumulative Payment (Percent)	Cumulative Time (Percent)
1		1.850	22.200	20.000
2		1.500	40.200	40.000
3		1.530	58.560	60.000
4		1.561	77.287	80.000
5		1.893	100.000	100.000

TABLE 2 Contract Extension Payment Schedule

Year		Monthly Payment Schedule (Percent)	Cumulative Payment (Percent)	Cumulative Time (Percent)
6		1.750	121.000	120.000
7		1.785	142.420	140.000
8		1.821	164.268	160.000

Short- and Long-Range Impact

TxDOT ventured into this type of contract to develop another tool in performing needed maintenance with limited resources. The initial reaction to this type of contract by TxDOT managers and employees was very negative. Concern was expressed about the impact on the morale of maintenance employees, the reaction from the public, the ability of the contractor to respond in emergency situations, and the anticipated higher cost.

Fears have been calmed by the communication, education, professionalism, and competence exhibited by the low-bid contractor. Generally, the bid was substantially lower than expected. Some unanticipated benefits that have the potential to influence the organization are some of the innovative approaches of the contractor. For instance, to respond to a snow-and-ice event, the contractor arranged for local agricultural fertilizer companies to use their equipment to distribute aggregate and deicing chemicals on the roadway. Not only was this equipment readily available, because of the bad weather and time of year, but it proved to be very effective in regulating the quantity of material placed. The contractor has also used some experimental materials with good success.

There was also concern expressed by small businesses about their inability to bid on the maintenance work. However, the contractor has subcontracted a large amount of the work to the same contractors who were doing the work previously.

The partnering sessions resulted in a good start for the contracts by opening lines of communication and introducing the stakeholders from all parties.

The long-range impact on TxDOT will be the development of an additional tool in the goal of maintaining the highway system.

Cost and Time Savings

Although TxDOT anticipated the cost of these projects would be higher than previous costs, the bids came in lower than expected. These contracts are very early in their life and the true cost cannot be determined until levels of service can be evaluated. The condition of the sections at the end of the contract period will play an important part in determining the cost-effectiveness of the contract.

There are a number of less tangible advantages to this type of contract from the management perspective. Less inspection is required because of a single contractor versus multiple contractors. Less documentation of quantities performed is required because of the lump sum payment method versus individual items of work.

Also department forces can utilize innovations, effective methods, and new equipment developed by the contractor. The contractor may be innovative in the use of alternative or experimental materials, which may prove their benefits for further use by the department.

Conclusion

The development of this type of contract provides another tool for transportation engineers in maintaining the highway system. It may result in cost savings to the agency and may provide the development of innovative methods, materials, or processes.

References

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Evolution of Contract Maintenance

Marshall L. Stivers

Contract maintenance has become a significant tool in recent decades that is used to some degree by most state agencies in the United States. Until the early 1970s, highway maintenance was mostly planned and executed by public highway agencies. Then, some highway agencies started contracting maintenance activities to private-sector resources. For the next 25 years many maintenance activities were outsourced in this manner. Some of the significant trends and projects that have occurred within the highway maintenance community are documented. It is hoped that documenting a composite of some of the various strategies tried by governmental agencies will help readers determine which methods may be applicable for their agencies.

Over the past several decades contract maintenance has become a significant tool that is used to some degree by most state agencies in the United States. Until the early 1970s, highway maintenance was largely planned and executed by public highway agencies. Then, a handful of highway agencies began to pilot the contracting of maintenance activities using private instead of public sector resources. During the next 25 years a significant amount of maintenance activities began to be outsourced in this manner.

The purpose of this paper is to document some of the more significant trends and projects that have occurred during the evolution of outsourcing within the highway maintenance community. It is hoped that documenting a composite of some of the various strategies tried by governmental agencies will help readers determine which of the methods may be applicable for the circumstances within their agencies.

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The Trend

During the 20 years from 1973 to 1993 the trend of several highway indicators very clearly explains the situation in which most highway agencies currently find themselves. This trend is demonstrated by the change in the following items that were measured during the period:

- Road and street mileage increased 2.6 percent,
- Population increased 22.0 percent,
- Licensed drivers increased 42.5 percent,
- Motor vehicle registrations increased 56.4 percent, and
- Vehicle miles traveled increased 74.9 percent.

In recent years this trend has intensified the problems of the highway maintenance community because of the "blessings" of a booming economy, increased transportation funding, the trend toward downsizing, and more and heavier trucks. As a result of these trends many highway agencies are not able to provide their customers with an adequate level of service. Although funding levels for routine maintenance are generally at an all-time high, in most agencies staffing levels have not kept pace with increasing workloads. Many agencies are not allowed to replace maintenance employees who have left, and instead they are encouraged to change the way the remaining employees think and act. Although some benefits were achieved in this self-improvement process, workloads continue to increase too fast for employee productivity improvements to keep pace.

Recognizing the need for assistance for conducting routine maintenance within highway agencies, private industry developed the capability to accept some of the highway maintenance workloads. This capability enables a highway agency to contract with a private firm to perform activities necessary for routine maintenance of a specified group of highways. Usually this service is performed in the same manner provided by the agency, for the same or an even smaller total cost. As the trend toward increasing workload and a diminishing workforce continues, more agencies are now considering outsourcing as a tool for providing services to the motoring public.

Currently outsourcing is generally being accomplished by one of two methods. The first method can be called activity based, which involves obtaining unit prices for each activity to be contracted. The second method usually involves a specific area or region being set aside for total routine maintenance to be accomplished by a contractor. The second method can be further subdivided into areawide bundled bids and comprehensive asset management contracting.

An additional feature of outsourcing is also being offered, which is generally known as at-risk projects. In this scenario, contractors guarantee the agency a fixed price for the life of the contract (typically 5 to 7 years), and the contractor assumes all risks associated with the project at no additional cost. These risks may be the result of damages to the highway infrastructure caused by fire, flood, wind, snow, vehicle crashes and accidents, and so forth.

For any of these methods to function, it is necessary for the agency to be assured that the roads being outsourced are maintained in a safe and passable condition to protect the investment in the highways. Similarly, the level of service provided by the contractor must be equal to or greater than the level provided by the agency.

Maintenance activities that are typically accomplished by contracting include all routine periodic maintenance activities involved in repairing highways and bridges, including pavement surfaces, shoulders, roadsides, drainage facilities, bridges, tunnels, signs, markings, lighting fixtures, traffic services, mowing, litter and debris pickup, and snow and ice control. The operation of roadside rest areas, movable span bridges, and various minor construction activities are also typically handled through maintenance contracting.

Activity-Based Unit-Price Contracting

During the 1970s and 1980s, most maintenance contracts were activity-based or unit-priced contracts. These unit-priced contracts stipulate that a contractor will be paid "*x* dollars" to perform one unit of "*y* activity." Activities that are typically accomplished by unit-price maintenance contracting include repairing highway surfaces, shoulders, drainage facilities, signage, markings, lighting, and signal operations as well as roadside maintenance such as mowing and litter pickup.

Awarded as single contracts to perform one activity, unit-price contracts are a common and useful tool for departments of transportation across the country. Although they allow an agency to respond to specific manpower and equipment shortages, the administration of this type of contract requires significant inspection costs to ensure that full value is received. Issues involving poor quality of work, lateness of the contractor performing the activity, defaulting and subsequent reassignment of agency resources, and contract readvertisement are some of the difficulties that may be encountered with this type of contracting. Unit-price contracts still have a proven value for some agencies who need assistance on a limited basis.

Areawide Bundled-Bid Contracting

The next step in the evolution of contract maintenance occurred in the late 1980s with the advent of areawide maintenance contracting. Areawide contracting has evolved in basically two stages. The first stage involved single-service unit-priced contracts. The next stage occurred when areawide contracts bundled essentially all the routine maintenance functions commonly required. A few examples of the types of contracts that have been tried by some state agencies are described in the following sections.

Massachusetts

The Massachusetts Highway Department (MHD) piloted an areawide contract in 1992 that bundled essentially all routine highway maintenance and drawbridge operation in Essex County. MHD chose this region because it offered an ideal mix of highways, city streets, and drawbridges for testing private maintenance services. The $4.08 million contract, which encompassed 611.5 road kilometers (380 road miles), was for all the functions of the District 5 maintenance office except snow and ice removal. The specific services provided in the contract include the following:

- Highway maintenance: cleaning, maintaining, and repairing roads, sidewalks, curbs and berms, ditches, slopes, guardrails, and drainage systems.
- Bridge maintenance: repairing and maintaining bridge decks, cleaning bridge seats and drainage systems, and doing other minor concrete repairs.

- Roadside maintenance: tree trimming and removal, sight distance clearing, and mowing.
- Traffic maintenance: maintaining and repairing traffic control equipment and lighting systems; painting stop lines, crosswalks, and road legends; and installing regulatory and warning signs.
- Drawbridge operations: operation and routine maintenance of drawbridges.

The request for proposal (RFP) issued by the MHD specified a method to price unforeseen services not itemized in the contract and also included detailed descriptions of repair methods, material specifications, and quality standards. The individual services were specified in existing state highway maintenance documents and a set of supplemental provisions and specifications for Essex County. These standards were quite detailed, defining everything from the required consistency of various forms of concrete to the composition of bridge paint. MHD personnel would continue to be responsible for ensuring the contractor adhered to the standards.

Available information on the MHD experience with the Essex County contract has been derived from a document prepared by the John F. Kennedy School of Government. In it is a statement about an assessment of the details contained in the contract: "The desired ends for the contracted services are fairly easy to define: satisfactory performance of routine maintenance, timely repairs, and proper operation of the drawbridges. There are a limited number of ways to accomplish these ends successfully, and as the above discussion of the contract indicates, the MHD has in many cases specified the preferred means. If anything, the contract errs on the side of being too specific about the means and could perhaps stifle innovation. An improved asphalt for patching potholes, for instance, could conceivably be unusable under the terms of the contract. The department has properly left many of the operational details, such as work crew size and equipment requirements, to the contractor's discretion."

The John F. Kennedy School of Government documented the success of the pilot program, concluding that privatized highway maintenance services were over 20 percent more cost-effective than their public counterparts. To compete, three unions formed a coalition, developing proposals to be competitive with private industry. Through the additional training and efficiencies among agency staff, overtime decreased 70 percent and sick leave decreased 50 percent in the first year. Currently the workload is being split about 50/50 between public and private contractors.

Florida

In 1994 the Florida Department of Transportation (FDOT) used extensive contract maintenance successfully, by combining several small activity contracts into one large contract. This change evolved from activity contracting to regionwide maintenance contracting when a pilot contract on I-95 in Jacksonville was awarded. The changes continued when all [about 177 km (110 mi)] the state highways within Nassau County were awarded in 1997 for a 3-year contract using activity-based prices. In essence this combined many smaller contracts into a single contract with FDOT issuing work orders on a daily basis. The documented benefits from this program included the following:

- Cost savings of about 10 percent,
- Reduced FDOT administrative costs of 70 to 90 percent, and
- Improved quality assessment rating of 30 percent.

The advantages to awarding contracts of this type include having one contractor perform multiple activities throughout the limits of a specific project. The agency inspector issues a work order when needed and the contractor responds as required. Agency costs for administration are lower because of a reduced number of contracts to advertise and inspect. Because this type of contract is much larger in scope than single activity-based contracts, the overall price compared with multiple contracts is usually lower because of the economies of scale achieved by the contractor. In this environment, the contractor can anticipate the multitasking of employees and equipment to perform several activities and pass the savings on to the agency.

The disadvantages of this type of contracting are that the contractor has no incentive to perform less work. These contracts usually specify that payment is by work accomplishment, not innovation, and once the contract is awarded any savings for doing work more efficiently remain with the contractor. Innovation may also suffer if work orders are issued for traditional methods (pavement striping with paint instead of longer-wearing materials) that may accomplish the same effect at a cheaper cost. Although this method of contracting has proven more advantageous than activity-based unit-price contracting, FDOT is now trying to improve even further. In the next section, the evolution of maintenance contracting that is being tried by FDOT is discussed.

Comprehensive Asset Management Contracting

Virginia

The Virginia Department of Transportation drastically changed the paradigm in July 1997 when it contracted for 402 km (250 mi) to be the total responsibility of a contractor. The impetus for the $132 million contract was the state's public-private transportation act, which encouraged creative approaches involving the private sector. The contractor performs all the ordinary maintenance activities to a predetermined level of service. Planning, scheduling, overseeing, and execution are the responsibility of the contractor under this program. This contract, which is for a 5.5-year pilot project with an optional 5-year renewal, includes all routine maintenance activities, incident management, snow and ice control, and major pavement and bridge rehabilitation.

The contract, which is a lump sum guaranteed maximum price, limited risk acceptance, fence-to-fence responsibility, has afforded a multitude of benefits to the department such as the following:

- Guaranteed cost savings of about 17 percent versus in-house,
- Reduced capital cost outlays,
- Ensured outcomes and consistency,
- Guaranteed maximum price,
- Flattening out of peak workloads,
- Obtaining specialized skills or equipment,
- Increased levels of service,
- Limiting the agency staff and administrative requirements, and
- Providing a single point of contact for the agency.

Although the project received some initial opposition from industry, it is now in its third year and is beginning to become more accepted. Some lessons have been learned from this experience, however, including the following:

- Year 1
  - Difficulty in monitoring time performance,
  - Statistical issues regarding sampling of rating sites,
  - Missed targets,
  - Recovery plan not articulated, and
  - Improvement in incident response was necessary;
- Year 2
  - Startup was smoother,
  - Acceptance of concept by the field,
  - Snow and ice control began, and
  - Recurring issues on I-95 (incident response, traffic control).

The lessons learned from this type of process better explain how to monitor timeliness requirements, establish better cost accountability, establish a more positive sampling technique, establish competitive bidding on the next contract, and provide a longer commitment for the contract to establish better prices.

Texas

In fall 1999 the Texas Department of Transportation (TxDOT) awarded $32 million for the complete maintenance and operation of 246 km (153 mi) of Interstate highways, including existing appurtenances and future additions. The 5-year contract, with two extensions if both parties agree, includes mainline roadways, frontage roads, shoulders, ramps, intersections, roadsides, bridges, rest areas, picnic areas, weigh stations, and traffic operations. The intent of the project was for the contractor to relieve the department of all duties traditionally performed by the department in maintaining and operating the highways. It is anticipated that no change orders, except state or federal statutes or catastrophic event emergency reimbursement, will be executed during the course of the contract.

Each month TxDOT determines whether the contractor is meeting the required standards. In addition, the contractor must constantly monitor the condition of the highway. If the contractor or engineer discovers a deficient section, the contractor reports to the engineer measures that will be taken to correct the situation. Standards have been developed and will be monitored for the following areas:

- Asphalt surfaces (travel lanes and shoulders),
- Concrete pavement (travel lanes and shoulders),
- Vegetation management,
- Landscaped areas,
- Litter and debris pickup,
- Sweeping,
- Graffiti removal,
- Picnic areas,
- Rest areas,
- Tree and brush control,
- Drainage,
- Removal of illegal signing and other encroachments,
- Mailbox installations,
- Bridge maintenance (railing, deck, superstructures, channels),
- Embankments,
- Traffic operations (loops, signs, highway lighting, pavement graphics, pavement markings, RPMs, traffic buttons, impact attenuators, overhead signs), and
- Snow and ice control.

The bid proposal document contained the statement "This is an experimental project." Further wording in the document indicates the contract can be terminated within 30 days if both parties agree. A proposal form to identify work was required, which contained the following information:

- The location and description of the proposed work,
- An estimate of the various quantities and kinds of work to be performed,
- A schedule of items for which unit prices are requested, and
- The time within which the work is to be completed.

The official total bid for this proposal was determined by multiplying the unit prices for each pay item by the estimated quantities shown in the proposal and then totaling all the extended amounts. This total became the "total bid amount" and was to be full compensation for the work for the 5-year period of the contract.

The bid proposal document stated, "When the final quantity of work done under any major item of the contract is less than 75 percent of the quantity stated in the proposal, the adjusted unit price to apply to the final quantity of work performed under the item will be determined by multiplying the unit price bid by the factor shown below."

Percent Decrease	*Factor*
25 to 50	1.05
51 to 75	1.15
76 to 99	1.25

The bid proposal document also stated, "In no instance shall the product of the adjusted price and the final quantity of work exceed the product of the original contract unit price and 75 percent of the original contract quantity, and in no instance will the unit price be adjusted to more than 125 percent of the original contract unit price." The contractor's payment may also be reduced if any of the project limits requires major rehabilitation work during the term of the contract. The reason for this is that maintenance of the roadway becomes the responsibility of the rehabilitation work contractor, with the maintenance contractor having no work requirements within the limits of the rehabilitation project.

A contract requirement was for the contractor to begin work within 30 days of being declared the successful bidder. After more than 6 months of experience by both parties, TxDOT believes this requirement should be extended to at least 3 months on future contracts of this type. The current belief is that the project would gain better acceptance by both the state and the contractor if a longer transition period were available.

Even though it is early in the process, TxDOT was asked to discuss positive and negative reactions to the performance of the contract so far. The comments received appeared to be positive reinforcement for the process, with a few observations as follows:

- Ice and snow control by the contractor was very good. Compared with TxDOT performance, the contractor raised the level of service above what the agency normally delivered.
- Potholes, which would be repaired immediately by TxDOT, remain in place longer because the contractor, for efficiency, tends to wait until more potholes develop before scheduling work crews to make repairs.

District of Columbia

The District of Columbia Public Works Department (DCDPW) recently awarded a 5-year project for the National Highway System (NHS) routes that fall within the city's boundaries. The project involves a unique partnership between the DCDPW and FHWA, who are providing oversight and assistance for the project. Part of the oversight duties involved selecting an engineering support consultant company to take a complete inventory of the many roadway assets and their condition located within the NHS rights-of-way. Once this was completed, a private contractor was selected using a "best buy process" for a 5-year performance-based maintenance contract to maintain the highway infrastructure. Working with FHWA and the engineering support consulting company, the DCDPW has identified and developed measurable performance standards for the infrastructure items to be maintained by the contractor. It is believed that a measure of the effectiveness of the program can be obtained by implementing measurable performance standards and annual objective system evaluations and reporting techniques.

The NHS project is designated as a demonstration project and eventually may be duplicated in other areas of the District or in other major urban areas that require preservation and maintenance work and have limited public agency staffing. The total NHS segments in the District are about 553.5 lane kilometers (344 lane miles), which consists of the city's most important and heavily traveled roadways. A contractor for the 5-year contract has been selected, and the project is proceeding toward award. The contract is expected to have a total value of $73 million, and work is anticipated to begin on or about June 10, 2000. The following activities are included in the scope of work:

- Pavement maintenance,
- Drainage maintenance,
- Roadside and landscape maintenance,
- Bridge maintenance,
- Tunnel maintenance,
- Snow and ice control, and
- Traffic control and safety maintenance.

The tunnels on this contract, which amount to about 20 percent of the total bid price, cause it to be somewhat unique among the more traditional asset management style of routine maintenance contracts. Typically most routine maintenance contracts are exactly what the title infers—routine maintenance—with an occasional pavement and bridge rehabilitation added to some projects. The four tunnels in this project, however, require a significant rehabilitation effort that is expected to be completed within 1 year of the start of the contract. Once the tunnels are rehabilitated they will be maintained at the specified benchmark until the end of the contract.

For this project, the development team evaluated and quantified the condition of the existing asset elements to establish the existing baseline condition. Based on this information the team established benchmarks for each of these conditions. The contractor was then required to respond to this information with ideas about how to proceed. The contract was not prescriptive in the approach to take in preserving the system and sought to promote innovation from the contractor in recommending actions.

Some of the wording made available to contractors about the condition of the tunnels included the following:

- "The tunnel was rehabilitated completely in 1997, however significant needs remain. This is partly because not all problems were addressed by the rehab. And partly because the new systems have not been maintained. Needs may be as high as $3 to 4 million."
- "Drainage problems still occur, but solution is unclear (sources may be the Labor Building, reflecting pool, groundwater). Some water damage is present, but no impact on the structure."
- "New computer control system was put in, but is not functioning. Lighting system is operating in manual mode."
- "Low clearance results in significant numbers of occurrences of damage to lights—possible need to redesign lighting to avoid this problem."
- "Fans haven't been well-maintained, some are not functioning properly (motor problems)."
- "CO monitoring system replacement—never functioned properly."

As can be seen from the items listed, the concept of routine maintenance contracting has taken a new twist, which may open up an entirely different method for agencies to outsource work. Somewhat like the design, build, and maintain concept that is currently being considered by many agencies, this new direction could be entitled redesign, rebuild, and maintain.

Florida

On May 1, 2000, FDOT opened bids and declared an apparent successful bidder for a 409-km (254-mi) contract on the I-75 corridor that spans the boundaries of five districts. Once the contract is executed, FDOT will oversee the maintenance management program and conduct evaluations based on performance specifications established in the contract. In the RFP issued for the contract, the following statement was included: "The use of performance specifications, which effectively transfers day-to-day managerial and administrative responsibility to the contractor, with oversight by the FDOT was chosen because methodology specifications would require the FDOT to perform extensive contract administration consisting of work identification, work assignment, inspection and documentation." The anticipated starting date for the $73.5 million contract is July 1, 2000. The contract, which is for a lump sum amount, is payment in full for the 7-year duration of the project. The lump sum price for a second 7-year period (extension) is specified as being the first period price plus 15 percent. Both parties must agree to the second 7-year period for it to be extended.

The project includes all components of the transportation facility (including interchanges, crossroads, and ramps; canals; and storm water management) within the limited access right-of-way. The contract will have a single project manager to interface with the contractor. Requirements of the contractor are to achieve and maintain a maintenance program rating (MRP) of 80. All elements (roadway, roadside, traffic services, drainage, and vegetation/esthetics) shall have a MRP of 75 or above and each characteristic shall meet the desired conditions a minimum of 70 percent of the time.

Proposals were evaluated and graded in accordance with the criteria detailed below and, as indicated, give each proposer a percentage of the 65 points based on their price versus the low bid price (which gets all 65 points):

- Technical proposal (100 points): Evaluation is based on the proposer's executive summary, management plan, and technical plan for understanding the project, qualifications, approach, and capabilities, to ensure a quality project.
- Price proposal (65 points): Price evaluation examines the prospective price without evaluation of the separate cost elements and is conducted through the comparison of the total price submitted for the 7-year contract period. The criterion for the price proposal was based on the following formula:

$$\text{(low price/proposer's price)} \times \text{price points} = \text{proposer's awarded points}$$

Innovation and contractor methods of efficiency will be passed on to the agency through the competitive bid process. Although the agency has not had time to evaluate all aspects of the bids as of this date (May 1, 2000), savings of about 15 percent are anticipated by utilizing a private contractor compared with FDOT's current method of getting work accomplished.

Mississippi

The Mississippi Department of Transportation requested expressions of interest from contractors interested in asset management of about 209 km (130 mi) of US-78.

The project, which was anticipated to last for a 5-year term, includes all assets within the no-access right-of-way on US-78, its interchanges, overpasses, and underpasses. The successful contractor is expected to keep the roadway at or above predetermined performance standards.

Each expression of interest was to contain an asset management plan consisting of evaluation methods, repair procedures, and detailed maintenance standards for performing the following items and their corresponding subitems:

- Asphalt roadway maintenance,
- Concrete roadway maintenance,
- Roadside maintenance,
- General physical maintenance,
- Traffic service maintenance,
- Drainage maintenance,
- Snow and ice control,
- Shoulder and approach maintenance, and
- Bridge maintenance.

The project will not include major bituminous overlays, bridge or structure replacement, or concrete overlays, but it will include concrete punchout repair and mechanical asphalt pavement repair.

Each asset management plan should include a complete initial inventory of all assets and a detailed reporting system, which should be documented by monthly reports of all work done, and also an annual report—all for the purpose of evaluating the overall effectiveness of the pilot program. The plan should also include responses to emergency situations.

Responses to the advertisement of this project were due in September 1999. An apparently successful firm was identified from the expressions of interest and negotiations started. To date no contract has been signed.

Conclusion

In the past 30 years, contract maintenance has evolved from its early infancy stage of single-service unit-priced contracts into full-service asset management contracts. Industry is now beginning to understand the needs of agencies and organizations are being created to meet these new opportunities. As competition increases, better pricing and service availability will most certainly become available. As this evolution continues, what the predominant model will be remains to be determined. But one thing appears certain: a public-private partnership will be an essential element for most governmental agencies to accomplish their increasing workload requirements.