With this second issue of the IRF Examiner, the International Road Federation confirms its role as the leading provider of applied knowledge in areas of vital importance for the global community of road professionals. This vision has been carried out year after year, culminating with the 17th IRF World Meeting & Exhibition which welcomed more than 2,000 delegates from 92 countries in Riyadh, Saudi Arabia. The wealth of knowledge accumulated during the World Meeting has been the driving force behind our decision to launch the IRF Examiner as a freely available resource for the industry.

Increased vehicle travel, growing population, aging physical infrastructure, and escalating maintenance and operating cost all put demands greater than ever on the transportation system. There is much for us all to learn from the research and successful programs presented in this edition of the IRF Examiner.

H.E. Eng. Abdullah A. Al-Mogbel
IRF Chairman
Mayor of Riyadh, Kingdom of Saudi Arabia

Adopting effective Road Asset Management practices sustains pavement longer, helps cut pollution and offers users a safer driving environment. These should all be crucial priorities for road engineers, highway planners and network managers globally. Chronic underfinancing of road infrastructure risks endangering this important asset, yet many road authorities lack data on the value of their network and the state of their roads.

As the global leader in advocating for better, safer and environmentally friendly roads, the International Road Federation has long advocated for new approaches to asset preservation, in particular through the use of new asset survey technologies and performance-based maintenance contracts. I am pleased to present the second volume of the IRF Examiner, which aims to equip road managers with a better understanding of the state of the art in sound highway management practices.

C. Patrick Sankey
IRF President & CEO

This issue of the IRF Examiner covers a multitude of asset management-related papers addressing the collection and use of essential data, enabling transportation agencies to forecast future condition and minimize the life-cycle costs for managing and operating roads, bridges, tunnels, drainage structures, roadside features, and other physical assets.

The IRF has established an asset management committee to help transportation agencies address issues related to asset management training, resources, technology transfer, and research. The group has been very active lately. A global survey of asset management practices was completed in 2013 with responses from more than 60 countries received. The committee had a very strong presence at the 17th IRF World Meeting & Exhibition in Saudi Arabia, held in late 2013, with more than eight session covering asset inspection, making the case for funding, performance-based decision making, maintenance and management systems. The asset management committee is pursuing the development of a white paper to address the importance of asset management on a global scale. The IRF also sponsors asset management webinars, conferences, and training sessions. If you are an IRF member, please join us as part of the asset management committee and help set the direction of asset management for the future.

Prof. Omar Smadi
Iowa State University
Chairman, IRF Committee on Asset Management
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ABSTRACT

Transportation asset management (TAM) has gained ground as an effective decision-making tool and process that agencies have continued to explore without a formal requirement. In July 2012, the U.S. Congress reauthorized national surface transportation funding with Moving Ahead for Progress in the 21st Century (MAP-21), the first national transportation legislation with a strong emphasis on performance-based planning and asset management, creating a mandate for all agencies to implement TAM within a specified timeframe. This paper presents a critical review of the historical development of TAM in the U.S., highlighting how this concept has been shaped by Federal, state and local policies over the years. The paper assesses the contents of transportation legislation, identifying strengths and weaknesses of the policies and implications for transportation infrastructure performance, while highlighting successful implementation strategies and challenges faced in policy implementation. The results highlight lessons learned in policy implementation to provide high-performance infrastructure, revealing factors that can influence the effectiveness of TAM policy implementation, to meet the requirements of MAP-21.

INTRODUCTION

Transportation Asset Management is “a strategic and systematic process of operating, maintaining, and improving physical assets, with a focus on both engineering and economic analysis based upon quality information, to identify a structured sequence of maintenance, preservation, repair, rehabilitation, and replacement actions that will achieve and sustain a desired state of good repair over the lifecycle of the assets at minimum practicable cost” (1). This definition, much like many others developed by different organizations around the world, presents a comprehensive explanation of the concept of asset management, highlighting the basic principles of TAM which include: (i) a systematic evaluation of asset needs and available resources, (ii) consideration of entire asset lifecycle, (iii) combining engineering and economic principles, (iv) data-driven decisions and investments, and (v) efficiency and cost-effectiveness as primary outcomes (2).

Unlike pavement and bridge management, TAM encompasses all classes of infrastructure within an agency’s jurisdiction. With the objective of upgrading, preserving and maintaining infrastructure over the lifecycle, TAM systems and the process of managing infrastructure assets can guide an agency in efficiently allocating resources. One of the most important components of a TAM system is the continuous evaluation of the progress towards an agency’s goals, in a feedback loop driven by performance monitoring. Figure 1 below shows the components of a generic asset management system, including this feedback element.
TAM DEVELOPMENT IN TRANSPORTATION POLICY

The principles of TAM have existed in the transportation industry for many years, albeit not explicitly. The beginning of asset management in transportation has been traced back to the American Association of State Highway Officials’ (AASHO) Road Tests conducted in the late 1950s to determine the relationship between structural designs and expected loading over pavement life (4). The results of this experimental period led to the introduction of performance measurement and prediction and, ultimately, pavement management systems (PMS). Bridge management systems (BMS) followed about a decade later, supported by Federal legislation, after the 1967 collapse of the Silver Bridge between Ohio and West Virginia (Ref 4 from original). In the years following, Federal legislation inherently expanded and encouraged asset management principles, leading up to the Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991 which shifted focus from highway expansion to maintenance and preservation. ISTEA was very explicit in including asset management principles, going as far as to mandate six management systems, a requirement that was later rescinded (11, 12).

In 2012, the United States Congress reauthorized national surface transportation funding with the Moving Ahead for Progress in the 21st Century Act (MAP-21), the first national legislation to contain strong and clear requirements for performance-based planning and risk-based asset management. This development in transportation policy represents an important formal shift from a worst-first maintenance and investment strategy to a more deliberate, outcome-based investment strategy.

Similar to ISTEA, MAP-21 introduced a momentous change in the way transportation authorizations had been done by creating explicit, streamlined, performance-based and multimodal programs (6). Whereas previous legislation lacked direct and clear national goals, MAP-21 specifies seven surface transportation goals that agencies are to work towards, increasing accountability and transparency, and making way for more efficient investments and decision-making through performance-based planning and programming (5, 6). MAP-21 is the first legislation to specifically mention and require the development of a risk- and performance-based asset management plan for all aspects of transportation, including public transportation and freight. With funding provided for implementing asset management programs, the requirements in MAP-21 are very clear, even down to the specific contents of a TAM plan. If a transportation agency fails to develop a performance-based program, using asset management and performance measurement principles, according to the provisions in MAP-21, the consequences include a reduction in Federal funding for transportation projects (7, 6).

While in rulemaking to develop the guidelines for MAP-21 implementation, the United States DOT (USDOT) through the Federal Highway Administration (FHWA) continues to host a series of informational webinars (some in collaboration with AASHTO) to facilitate a national dialogue on the main changes in transportation legislation introduced by MAP-21 (8).

Over the years, transportation policy has had asset management principles embedded in the general concepts, but in some cases, explicitly required. Many of these legislations had similarities in terms of both general characteristics and specific details which either led to effective implementation of the mandates in the policies or presented barriers for implementation. MAP-21 marks the beginning of a new era in transportation policy and planning and the general way of doing business in the United States transportation industry. The new formal requirements for TAM bring in a number of implications for the success (or failure) of TAM growth, that did not exist for previous legislation. So what will be the effects of these unique changes in Federal transportation policy and how can they be effective in encouraging successful implementation of asset management programs? In order to answer these questions, it is useful to highlight the accomplishments and opportunities for improvement from previous Federal legislation, identifying factors that can lead to successful implementation.
FACTORs THAT INFLUENCE TAM POLICY IMPLEMENTATION

Financial Support for Mandates
Implementing an asset management program requires some significant investment from agencies for components such as the management system or software tool, data collection and inventory efforts, staff training and increasing organizational capacity, refining organizational structure, among other necessary processes. The limited success of the management systems mandated in ISTEA has in many cases been attributed to the lack of adequate funding to support the development of those systems (9). Federal funding reduces the pressure on a state or local agency to divert funds from other agency business into a concept that they may not necessarily have completely bought into yet. One of the main benefits of infrastructure management is the cost savings associated with preventive maintenance which leads to the avoidance of infrastructure failure; however, this cost savings is a long-term benefit that is not immediately realized. In some cases, agencies may simply not have the resources to implement a required mandate without significant effects on other aspects of their operations. Financial assistance offsets the gap between initial capital investment and the return that will be realized in the long-term as a result of strategic management practices (10).

Industry-Wide Ownership and Understanding
Asset management systems present a new way of making decisions that are typically made based on engineering judgment and political influences in the transportation industry. One of the common barriers to implementing pavement management systems and bridge management systems (BMS) before they were mandated was a general resistance to changing this decision-making structure by depending primarily on data and other technical details (10, 11). This challenges agencies’ standard operating procedures (SOPs) and raises justified questions on the reliability and authority of the systems and the models used to create them. In the same way, program implementation presents concerns related to both organizational structure and capacity, challenging the way they have previously existed. During the ISTEA period, difficulties related to organizational structure manifested in scenarios where different divisions within an agency were required to communicate with each other, which had never occurred before (12). Organizational capacity issues related specifically to the level of expertise and familiarity with asset management systems also occurred within the state and local agencies, and to some extent, even the USDOT (24). Without improved understanding and ownership of TAM, agency implementation incorporating these necessary changes in SOPs and organizational characteristics will not be effective. Increased industry-wide ownership of TAM can reduce some of this opposition. The AASHO road tests in the 1950s helped to accomplish industry-wide ownership of PMSs, to some extent, by contributing to the overall understanding of the underlying concepts. For present-day TAM, some agencies have conducted pilot studies illustrating the feasibility and bolstering agency-wide understanding. In addition, establishing clear national goals can elucidate the importance of TAM systems to stakeholders. A 2011 report by Transportation for America (5) proposed a number of challenges in transportation policy, including the lack of a national vision and clear goals to move surface transportation forward. The existence of clear goals and objectives for TAM, specifically, defines its use and makes it more than just another requirement that agencies must fulfill in order to be funded.

Institutional Commitment and Technical Support
During the highway boom, as road maintenance started to become a more important issue, the Office of Maintenance was formed. Similarly, the emergence of asset management in the 1990s led to the formation of the FHWA Office of Asset Management even without a Federal mandate. These institutional changes by the administrative arm of the government reflect the Federal government’s commitment to these concepts, encouraging states and local agencies in their implementation of management systems. Besides setting an example for these agencies, a specific office becomes directly responsible for all things related to TAM implementation and is able to provide support to agencies, whether technical or otherwise.

In the same vein, industry organizations such as TRB and AASHTO have shown support for asset management through the Task Forces and Committees they established, whether to host conferences, webinars or training sessions. These offices and committees contribute to the success of implementation by creating an environment to facilitate discussion on the topic, providing resources to guide operation and assist in building expertise within the agencies. Essentially, these organizations become advocates for asset management, communicating the importance of these practices to the stakeholders of the transportation industry, especially the public and the legislative arm of the government.

Other Implementation Logistics
When ISTEA was enacted, there were several challenges that agencies faced in the short time that management systems were mandated. For one, the requirements
mandated did not align very well with the management systems that already existed (PMSs and BMSs) causing agencies to have to consider significant changes in their existing practice (12). In developing and implementing policy, it is important to consider the order of events. PMS and TAM policy grew out of movements that had been occurring for years, where these systems already existed in different agencies. Creating a mandate established a standard for these systems which existed in varying form; however, ignoring the previously existing practices in order to create a uniform standard does not allow for effective implementation. With ISTEA, an additional challenge was that the time frame during which all six management systems were to be implemented was too short, especially in light of some of the organizational changes that were to result (24). The short time frame was one of the topics brought up in agencies’ initial response to the mandates and when the mandates were removed, some agencies continued development and implementation but at their own pace (36).

The NCHRP report on bridge management practices (11) discovered that after the mandates in ISTEA were repealed, the agencies that continued to operate BMSs did so very differently. This was driven by differences in the operating philosophies, approaches to planning, programming, and budgeting, the characteristics of the agency, their total transportation system and the infrastructure itself, and differences in the political, financial, technical and institutional environments. This observation points back to the long-standing argument that state agencies, specifically state DOTs, have innate differences that dictate the way they operate. This concept is supported by contingency theory, a class of behavioral theory which proposes that the best way to manage an organization and its performance is significantly dependent on the internal and external environment that the organization and its subunits have to operate in (14, 15). Allowing flexibility in the way policies are implemented contributes to the success and effectiveness of the process. Whether this is in terms of the data collection methods, software used or even performance thresholds, some level of flexibility in the mandates in order to address the varying needs of each state has been shown to be a useful strategy for success (11, 12, 16).

CONCLUSION

Contrary to popular belief, TAM has existed in some form since the very beginning of Federal-Aid legislation. While the concept has evolved significantly through the years, the underlying philosophy remains the same: to improve infrastructure condition and preserve the transportation system through cost-effective and strategic operation and maintenance with data-driven investment decisions. In recent times, clear and specific policies mandating aspects of asset management have proved to be catalysts of the development of these systems, encouraging their implementation. Nevertheless this process has not been without its fair share of challenges.

MAP-21, introduces a new era of infrastructure preservation by emphasizing risk-based, performance-driven asset management practices in all aspects of investment decisions within the various sections of the industry, including freight and public transportation. While changing the way business is conducted in the industry from process-based to outcome-focused, MAP-21 seeks to resolve some of the long-lasting issues associated with effective policy and program implementation. According to Nemmers (1997), agencies can successfully implement and operate asset management programs if they clearly understand and identify the real value of their assets, have trained personnel who are challenged to be economic managers in addition to their roles as engineers, determine service levels and commitments based on goals set by the public, and communicate effectively, how asset management can be used to address those goals (17). MAP-21 looks to have a successful implementation process because it is characterized by many of these factors, including clear national goals, flexibility in system operation especially related to performance measures and targets, and financial support from the Federal government. Finally, MAP-21 and the shift towards performance-based planning comes at a time when the industry in general has begun to adopt and take ownership of the concept of making the most out of limited resources in order to maintain and possibly improve system performance.
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Integrated Road Asset Management System: The Namibian Experience

Author:
Sophia - Belete Tekie
Road Management System Manager
Roads Authority Namibia
tekieS@ra.org.na

ABSTRACT
The Namibian Road Management System (RMS) has been in existence since the late 1980’s and can be used not only as a model for Africa and developing countries, but for the international community as well. Namibia went through a major road sector restructuring process for the Ministry of Works, Transport and Communications (MWTC) to form three new entities: the Roads Authority (RA), Road Fund Administration (RFA), and Roads Contractor Company (RCC). The RMS was included in the Roads Authority Act and plays a vital role in managing the countries road network. This paper will look at how the RMS of Namibia was developed and is being used in contributing to the management of the road network consisting of 45,645 km. Experiences gained from the strategic output of the World Bank’s model (HDM-4) and the integration of the model with the RMS are also evaluated.

ROAD SECTOR REFORM AND DEVELOPMENT OF THE ROAD MANAGEMENT SYSTEM
Namibia’s comprehensive definition of a RMS states: ‘A Road Management System is an all-encompassing framework, including both information processing and human resources, for the integrated management of the road network, including the determination and optimization of economically warranted projects, programs, strategies and budgets, for both development and maintenance’. The institutional arrangements for planning, designing, constructing and maintaining Namibia’s national road network have been restructured. Arrangements for the funding from the national budget are being replaced by funding via a Road Fund and a Road User Charging System. In addition to these functions, the operation of RMS is also considered to be an integral part of the principles of Road Sector Reform, which makes Namibia a very unique country.

The institutional reform has resulted in the establishment of the Roads Contractor Company, Roads Authority, and Road Fund Administration. These entities were launched in Windhoek July 2000 and operate under a governing Board of Directors. The Roads Authority operates under the auspices of the MWTC and manages Namibia’s rural roads network. The Road Fund Administration, under the auspices of the Minister of Finance, manages the road user charging system to secure and allocate funding to achieve a safe and economically efficient road sector not only for the Roads Authority, but also for local authorities. Finally, the Roads Contractor Company under the MWTC maintains and performs all physical works on the network.

The Namibian government has two tiers of government comprised of national and local levels. The Namibian Road Network is managed by the RA, a commercial entity, on behalf of the Ministry of Works, Transport and Communications. Ownership of the road networks remains with the government. With a population of two million, the size of the road network is considered to be rather large, but due to past imbalances about 60% of the population, mainly in the densely populated northern areas, does not have access within the two kilometer benchmark set forth by the World Bank. The government is trying to address imbalances by appropriating funding to the rural communities, but most do not meet the funding requirements. The Road User Fee is only used for so-called economically viable roads funded by the Road Fund Administration.

During the restructuring process the Department of Transport embarked upon a master plan for the RMS, a visionary document mapping out how the RMS of Namibia would be developed, funded, and implemented. It also contained a revolutionary Architectural System Design (ASD) document that defined the exact interfaces and integration requirements, taking into account local conditions. At the time ASD were not well known and Namibia was in the forefront of implementing good practices. The main beneficiaries were the road users as ASD systematized development and implementation plans.

The system has the capability to produce reports, graphs and maps with a click of a button. There is a
central database based on Sequel, a Microsoft product. Some of the developments of the new system are done on a PostgreSQL database mainly because of the web capability but also due to better functionalities with modern applications. The bandwidth in Namibia is still a challenge but may be overcome within a year or two. The rest of the systems will be redesigned for the new platform.

Each of the modules was developed using development life cycle, which is an ISO9001-certified methodology. It starts with having a user requirement specification (URS), then functional and technical design, system modelling, system implementation, training, and process redesign. The cycle repeats, improving each sub-module over time.

**FIGURE 1: Road Management System Wheel**

**TYPICAL OUTPUT FROM THE ROAD MANAGEMENT SYSTEM**

The Namibia National Road Network consists of 45,645 km of road, and is categorized according to surface type. The main arterial roads connect the major cities with bordering countries including South Africa, Botswana, Angola and Zimbabwe. Bituminous surfaced roads currently carry over 67% of the traffic. The remainder is comprised of main roads and district roads. The government maintains all these roads, while the RA manages them on behalf of the government. In addition, there are many farm roads (estimated at 20,000 km) in between the declared roads, but which are not shown on the map and maintenance is the responsibility of the owners through government subsidies.

Figure 2 clearly shows the deterioration of the paved road network from 1989 to 2012. Green is very good; blue is good; yellow is fair; red is poor; and purple is the worst condition. If no money is invested in the near future, the road network will be beyond repair and the road users will be greatly affected. Ultimately hurting the economy of the country, which is cause for concern.

**FIGURE 2: Trend of Deterioration on Paved Roads (Structural)**

**HDM-4 AND NETWORK INTEGRATION MODULE (NIM)**

Leaders envisioned incorporating the new Highway Development and Management (HDM-4) model of the World Bank during crafting of the master plan, at the time to the RMS. The team that developed the system, in Namibia, initially was engaged to assist in the Namibian HDM-4 implementation. The team of experts was comprised of seasoned Roads Authority technicians, engineers, RMS division staff members and Information Technology specialists as well as highly experienced engineers in construction, maintenance and modelling. In the past engineers and technicians went through all the modules of engineering, whereas now engineers specialize in a given field such as maintenance, planning or construction.

The results of HDM-4 versus the Namibian Modules provided a very interesting output that Namibia can share with the rest of the world. HDM-4 was used to calculate the purely economically warranted projects, and the Namibian model to calculate and provide a realistic budget, that includes economic, accessibility and maintainability factors. The subtraction of the two outputs gave a purely economic figure. Hence this method separated the government funding projects and the road fund successfully. An interface called the Network Integration Module (NIM) was developed to show the graphs, reports and maps in a user-friendly manner.

The Network Integration Module (NIM), the most important tool of the RMS sub-system, was launched and has succeeded in its objective. The NIM will collate...
the important summarised information from the various sub-systems of the RMS as well as manually entered information obtained from other needs not yet identified through a formal system. HDM-4 was incorporated into the NIM, as the best international tool already developed.

The RMS of Namibia and HDM-4 will complement each other, the HDM-4 component being funded by a donor. The project was completed in March 2003 with the first strategic output delivered in 2005. A comparison with the RMS of Namibia and the medium to long term Master Plan of 2003 developed by the Planning Division showed that HDM-4 results were not compatible. A re-calibration and re-analysis of HDM-4 brought about acceptable results. Segmenting road networks into homogenous sections now takes seconds instead of months through the NIM. Economical parameters are available by using the NIM and HDM-4. HDM-4 calibration factors are available as a standard after this study.

A five-year program, named the Tactical Analysis, was prepared using the combined HDM-4 and NIM. The results showed that the HDM-4 program preferred more upgrading and rehabilitation projects instead of resurfacing and re-gravelling projects (as was the case of the RMS modules of Namibia). Hence further analysis had to be made by adjusting the HDM-4 model to give results that are realistic. After several re-runs realistic results were obtained from HDM-4 and were successfully integrated with the NIM.

After the medium to long term Master Plan of 2009 was launched, the new data of PMS and unsealed RMS were used, and the whole exercise repeated. It took another full five runs and a re-configuration of HDM-4 to finally obtain reasonable results. It was very easy to conduct these runs as the NIM had all the modules to calculate and view the reports, graphs and maps. The better of two worlds was that HDM-4 (economically warranted projects) and the Namibian Models (based on appropriate standards) were utilized to determine a total budget that was used for planning purposes.

To segment the whole road network into homogenous sections and to prepare them for an HDM-4 run is a cumbersome exercise. NIM was created, as shown in the Figure 3 above, to ease this process. The HDM-4 data preparation button allows the user to create homogenous sections throughout the network. By clicking on the traffic volume, pavement type, climate, and other inputs the system puts the sections into cells. The strategic run is then done very quickly to get budget allocations for the various cells.

Some functionalities of the NIM

Once the data is prepared, the NIM opens the HDM-4 program and the data is imported. Subsequently the HDM-4 program is run, as shown in the Figure 4 below.

The Network Integration Module version 2 has been focusing on implementing a revised Strategic and Tactical / Program Output in line with the national transportation Mater Plan and the Vision 2030 of Namibia. Important aspects of the program with have strategic impacts are:

- Modelling of Vehicle Operating Cost
- Asset Valuation and Asset Registry of Roads
- Performance Indicators

After several runs of HDM-4 a reasonable output was obtained in comparison to the Namibian models. The strategic output was of more value than the program.
/ tactical output because of the low traffic volumes in Namibia among other reasons.

The NIM contains the following modules: Inventory Module, Quick Access Module, Integrated RMS Queries, Capture ‘new project details’, Budget Compilation, HDM-4 data preparation, Use HDM-4, Compile Work Programs, Compile Annual Reports and Asset Value. Not all the modules are working fully or developed due to some constraint issues, for example, the asset valuation. Namibia does not yet have a national policy on how to calculate asset valuation or how to place the roads on the balance sheet. Until that time, replacement value is used for calculation purposes. The other module is not yet fully functional and is lacking of the non-economic roads or social roads funded by the government to be captured and prioritized. That will be done in the future, but the capability of the system is available.

**CONCLUSION**

Despite persisting institutional challenges, the Namibian RMS is on the right track and can be used as a model for positive RMS implementation without spending excessive funding.

Systems like these are vital for sound decision making, which was one of the reasons why the commercialization process was initiated for making the RA more effective and efficient to serve the road users based on business principles. The vision of the Namibian RMS is to provide decision makers with sound decisions based on facts, and also to make the Namibian RMS an Internet based system. Although the availability of bandwidth is a major problem in southern Africa, the possibility of adding aerial photography will be regarded as an additional achievement for an already successful RMS program.

By doing so millions can be saved when implementing projects if the right decisions are made using the recommendations of the RMS. In Namibia the budget of RMS is less than 4% of the budget of Maintenance & Rehabilitation and Construction combined, which is good practice. Using both the Namibian RMS and the International Economic Model of the HDM-4, good output can be obtained but needs to be interpreted and used with caution and by understanding why some results can differ or why they can be similar. The important aspect is that the system must be simple, provide results that are realistic, and coincide with solid engineering judgment.

Lastly, various tools have been developed across the world, but what sets RMS apart is the usefulness of the information to make sound decisions. In the last five years the RA of Namibia has relied heavily on the output of the RMS that was utilized in making decisions that saved road users millions, and the impact has been significant. In the last few years the RMS has grown from a small laboratory system, to an organizational system which can be relied upon.

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Innovative Bridge Inspection Methods Using Image Processing and Infrared Technology

Author:
Masato Matsumoto
Executive Vice President
NEXCO-West USA, Inc.
m.matsumoto@w-nexco-usa.com

Co-Author:
Koji Mitani
President & CEO
NEXCO-West USA, Inc.
k.mitani@w-nexco-usa.com

ABSTRACT
Identifying appropriate applications for technology to assess the health and safety of bridges is an important issue for bridge owners around the world. Traditionally, highway bridge conditions have been monitored by visual inspection with structural deficiencies being manually identified and classified by qualified engineers and inspectors. With traditional on-site inspections, qualified inspectors perform close-up visual inspections and sounding tests, often from crane-suspended lifting cages or built-in inspection staging. The need for safer and more objective inspection methods calls for new innovations in bridge inspection technologies. One of the solutions for this issue is leveraging non-destructive technologies as well as experimental approaches for a more advanced and efficient inspection process. NEXCO-West, one of the major toll road operators in Japan has been working to develop efficient non-destructive highway bridge inspection methods using high quality digital image and Infrared (IR) thermography technologies. This paper describes the results of on-site applications of above technologies performed in conjunction with the University of Central Florida.

INTRODUCTION
Today, proper maintenance and management of deteriorating infrastructure under severe budget constraints have become serious issues for bridge owners. Traditionally, highway bridge conditions have been monitored by visual inspection with structural deficiencies being manually identified and classified by qualified engineers and inspectors. In Japan, NEXCO-West is performing periodic visual inspections for its expressway bridges at least every five years in order to monitor bridge conditions and expected future deterioration, as well as to prepare plans for further detailed investigations and maintenance actions (1). Similarly, in the United States, bridge inspectors in the field for bridge elements determine condition ratings of bridge components in the Federal Highway Administration (FHWA)’s Structure Inventory and Appraisal (SI&A) database. The information obtained from the visual inspection has been used to assist bridge owners in making decisions on bridge maintenance, rehabilitation, and replacement. However, the quality of inspection results obtained through the traditional inspection approach depends on the individual inspector’s subjective judgment based on his/her knowledge and experience, as well as varying field conditions. In addition, these traditional inspection procedures require significant investments in both time and labor cost. These factors support the necessity for research and development for more reliable, objective and efficient bridge inspection methods.

Under these circumstances, NEXCO-West has been applying innovative bridge condition assessment technology using infrared thermography and digital concrete surface imaging technology for its bridge structures. The infrared thermography technology is used before applying hammer sounding tests to detect possible subsurface deterioration including delamination or spalling of concrete. This provides bridge inspection engineers with targeted objective information from pre-screened areas of the bridge that needs closer attention for sounding tests. In traditional visual inspection approach, bridge inspectors prepare a summary of bridge condition factors and recommendations to bridge owners, submitted with the maps of crack existence.
and potential spall area. These maps are traditionally created manually, based on the sketch taken during the field data collection. In order to reduce the time required by inspectors in the field to make general structure condition assessments, NEXCO-West developed an innovative crack detection method using high quality digital image and image processing algorithm. Most of the information from the visual inspection and the sounding tests can be obtained by a combined inspection using both these technologies. Effectively combining these technologies can contribute to reduced time for on-site inspection and inspection report preparation, allowing engineers to have more opportunities to devote themselves to the engineering issues such as structural diagnosis and strategic rehabilitation planning.

The advantages of applying new inspection technology include:

- Overcome some shortcomings of human subjectivity
- Providing objective digital record for historical inspection data comparisons
- Improve efficiencies in bridge inspection resource application
- Identifying areas of bridge to be targeted for closer inspection and/or future monitoring

NEW INSPECTION TECHNOLOGY METHODS

Crack Detection using High Resolution Digital Imaging (HRDI)

Recently, significant progress has been made in the research and development of crack detection methodologies for efficient highway bridge inspection using high resolution digital imaging, HRDI, of the structures. NEXCO-West has developed a concrete crack detection technology using high quality digital image and image processing software (2). Sections of the concrete bridge elements are photographed by motion-controlled digital camera from the fixed locations, or high definition video cameras through mobile carriers such as the inspectors, vehicles, or boats. FIGURE 1 shows the automatic photographing system used for photographing from the fixed location. The digital camera is attached to the computer-controlled platform mounted on the tripod. Based on accurate matching between pre-photographed image and scanned drawings, the software automatically prepares a photographing plan. Each grid represents one snapshot for the high resolution frame. Once the photographing plan is completed, the software controls the motion of the platform, enabling the camera to automatically pan and tilt, and adjust the zoom for each high resolution frame. Once the field data collection process is finished, the software stitches the images collected from different angles at different distances and presents normal views of all structural surfaces, usually arranged as a single high-resolution composite image of the combined individual frames. The composite digital image is analysed by image processing to determine the structure’s current condition as related to crack size, location and distribution. Innovative crack identification algorithms can identify and quantify concrete cracks as narrow as 0.008”, which exceeds the American Association of State and Highway Transportation Officials (AASHTO) criteria (Current AASHTO guideline requires crack detection by conventional means to 0.01 inch, or 0.25mm for ‘Narrow’ cracks). Additionally, the crack size and length are determined by computer software and these quantitative characteristics are summarized in spreadsheet format. The obtained crack maps and supporting data are provided to engineers for their subsequent structural diagnosis and rehabilitation planning. A special advantage of this HRDI crack detection technology, with respect to crack identification and measurement, is the ease of maintaining a historical record of bridge cracks for use in monitoring crack propagation over time.

Infrared (IR) Thermography Technology

Infrared thermography technology is a non-destructive testing method to locate possible delamination and spalling of concrete through the monitoring of temperature variations on a concrete surface using high-end infrared camera. IR technology offers inspectors the advantage of being able to identify likely delaminated, spalled and inner voids areas from a distance of up to 60 meters with reasonable accuracy; thus avoiding the time and expense of gaining immediate access to the concrete
surface to conduct traditional sounding tests. The results of IR images provide bridge owners a reliable screening of potential concrete defects on concrete structures that have been traditionally obtained by more time consuming sounding tests. By applying IR technology to the concrete inspection process, inspectors can focus their hands-on sounding test activities on those areas shown through IR imaging as likely to be defective.

FIGURE 2 schematically illustrates the mechanism of infrared thermography methodology. The red line shows daily temperature variation for delaminated concrete, while the blue line shows the daily temperature variation for concrete in good condition. The delaminated concrete surface shows different temperature variation (see FIGURE 3). Infrared imagery technology is applicable during the periods when temperature differentials are detectable over time (IR imagery period A and B in FIGURE 2). It is not always possible to detect delamination of concrete only from the color variation of infrared imagery since the concrete structure itself tends to have a temperature gradient depending on location and orientation with respect to the sun. Akashi et al. (3) performed the statistical and analytical study on the relationship between characteristics of temperature variation and inherent damage of the concrete from the historical inspection database, and developed an automatic damage classification system that can classify the damage rate into three categories; the classification categories being “Critical” (crack caused by delamination reaches on concrete surface and immediate attention is required), “Caution” (crack exists within 2cm from the concrete surface and close monitoring is recommended) and “Indication” (Currently satisfactory) (see FIGURE 4). Raw infrared (IR) image data is filtered and rated into three categories by the software to indicate and evaluate the severity of subsurface defects in concrete structures. The monitor shows the raw, filtered and rated IR images at an inspection site in real time.

Additionally, the potential spall area is summarized in spread sheet format to provide quantitative data for bridge inspectors to prioritize the repair or rehabilitation works. In Japan, spalling of concrete debris from expressway bridges has become a serious issue. In order to prevent hazards to the third parties, comprehensive sounding tests have been performed on all potentially hazardous concrete surfaces exposed to motorist and pedestrian traffic from the 1990s. Using IR thermography technology, engineers can check the delamination and/or spalling of concrete about three times faster than they can by conducting conventional sounding tests because IR technology applications require significantly less staging to secure adequate site access and correspondingly less traffic control to collect the required field data. Concurrently IR versus traditional sounding tests offer a 40% cost savings. These techniques can also be beneficial to bridge owners here in the US.
**Deck Top Scanning System (DTSS)**

Deck Top Scanning System (FIGURE 5) is used to detect the surface defects and delaminated concrete from the topside of the bridge deck and includes the following two technologies:

- Line Sensor Camera for deck top surface defects such as cracks and potholes
- IR thermography for subsurface defects such as delamination (detecting possible future potholes)

The system can successfully detect the cracks with 0.3mm or greater. Since the system can scan the deck top while driving 80km/h, no lane closures of any kind is required during the field data collection. The system scans approximately 4.0m of deck width (one lane) from each run.

**A PILOT APPLICATIONS IN THE STATE OF FLORIDA**

**Deck Underside Inspection**

In order to validate effectiveness of the new inspection technologies, a pilot inspection project was conducted through a joint research effort with University of Central Florida (UCF). The objective of the research project was to investigate the technologies on the selected bridges to objectively characterize these deteriorated bridges with a university-government-industry collaboration, by exploring the use of novel image based technologies in a way that the information generated through these technologies will provide useful data for the inspection and evaluation of civil infrastructure systems. The Florida Department of Transportation (FDOT) District 5 provided expertise regarding operations, maintenance practices, real needs for improvement in the processes, and provided access to deteriorated bridges and inspection data, while UCF conducted research utilizing its knowledge in non-destructive evaluation and structural health monitoring. The efforts of this research project are to be designed to demonstrate the technologies, not only to validate the capability, but also to illustrate that they can be integrated into bridge owners' asset management systems with some minor adjustments. A sample bridge in Melbourne, FL was selected for the pilot application. Currently, the condition of the bridge is regularly monitored through established visual inspection procedures performed by FDOT certified bridge inspectors.

The Automatic Camera System photographed the underside of a concrete bridge deck. By magnifying the digital image on the computer, existing cracks were visually detected by an experienced engineer trained to interpret high resolution digital images (FIGURE 6). The detected cracks were categorized into three ranks depending on their widths (Rank 1: ≤ 0.25mm, Rank 2: 0.25mm to 0.76mm, Rank 3: 0.76mm or greater). After obtaining the digital crack map, the FDOT certified bridge inspector provided the hands-on inspection using a traditional crack width ruler in order to evaluate the accuracy of the new bridge assessment method. The widths of the cracks detected through the high resolution digital image matched with the actual hands-on measurements by crack width ruler for all the evaluated cracks.

**Deck Top Inspection**

In November 2012, bridge decks carrying Interstate 4 in Central Florida area were scanned while driving 80km/h by line sensor cameras and an infrared camera mounted on the truck. No lane closures of any kind were made during the field data collection. The bridge includes 3 spans carrying 4 lanes of the traffic. The 4th (left) lane has been added to the existed three lanes during the recent bridge widening project. Small potholes with the size of 12.5cm and cracks with longitudinal and transversal direction were detected from the scanned visual images obtained by the line sensor camera system. Some of the cracks make hexagonal shape and causing delamination/potholes within the cracking areas. The detected cracks were typically 0.3mm in width. According to the Bridge Inspectors Field Guide (4), cracks for reinforced concrete decks should be classified into three categories as shown in TABLE 1, and the NBI (National Bridge Inventory) specified “Distressed Area" is calculated for the rectangular area including “Moderate,” or “Severe” cracks. Most of the detected cracks on this bridge deck shall be categorized as 'Insignificant', and these cracks could not be detected by the traditional
visual inspection that is typically performed by the bridge inspectors overviewing the deck surface defects from the shoulder. The infrared thermography camera successfully detected the possible delamination in deck concrete as shown in FIGURE 7 (hatched in pink color). In order to find such deck subsurface defects traditional technique using chain dragging method requires lane closure during the inspection period.

**TABLE 1: Categorization of Crack Size (FDOT, 2008)**

<table>
<thead>
<tr>
<th>Crack Size</th>
<th>Insignificant</th>
<th>Moderate</th>
<th>Severe</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 1.6mm</td>
<td>1.6mm – 3.2mm</td>
<td>&gt;3.2mm</td>
<td></td>
</tr>
</tbody>
</table>

The percentage of areas of unsound wearing surface (spalls, delamination, delaminated temporary patches) is calculated for each span/lane of the bridge to prioritize the bridge repair/rehabilitation program. TABLE 2 can be used to determine the NBI condition state based on the percentage of unsound wearing surface. The deck scanning system can calculate the distressed deck surface area in terms of cracking and delamination. The percentage of distressed area for the total deck surface can be used as a quantitative index to determine the degree of deterioration for each span/lane of the bridge. If we could apply this deck scanning system to the corridor level inspection and determine the condition state for each span/lane of each bridge in the network, the bridge owner can use this information to prioritize the bridge deck repair/rehabilitation program and efficiently allocate the limited budget to obtain the maximum return on investment for the network level bridge management.

**TABLE 2: Proposed Threshold Values in Determining the Condition States**

<table>
<thead>
<tr>
<th>NBI Condition State</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condition State 1</td>
<td>The combined area of unsound wearing surface (spalls, delamination, delaminated temporary patches) is 2% or less of the total deck area</td>
</tr>
<tr>
<td>Condition State 2</td>
<td>The combined area of unsound wearing surface (spalls, delamination, delaminated temporary patches) is more than 2% but not more than 10% of the total deck area</td>
</tr>
<tr>
<td>Condition State 3</td>
<td>The combined area of unsound wearing surface (spalls, delamination, delaminated temporary patches) is more than 10% but not more than 25% of the total deck area</td>
</tr>
<tr>
<td>Condition State 4</td>
<td>The combined area of unsound wearing surface (spalls, delamination, delaminated temporary patches) is more than 25% of the total deck area</td>
</tr>
</tbody>
</table>

**SUMMARY AND CONCLUSIONS**

Using the proposed new non-destructive technologies, bridge engineers can quickly and efficiently obtain objective current bridge condition information that has traditionally been obtained by more time consuming and more subjective close-up visual inspections and sounding tests. The digital output of these NDE inspection techniques improves on-site inspection safety and objectivity and contributes to improved inspector efficiency by significantly reducing the amount of inspection time in the field. However, it must be noted that while most of the NDE or sensor technologies do offer new efficiencies and/or additional objective assessment results to the bridge inspection process, they are not a substitute for inspectors conducting on-site specific follow-up and detailed structure investigations. While improved efficiencies in bridge inspection methods resulting from the application of the above NDE technologies bring significant benefits to the overall bridge inspection process, they are not a substitute for the continued need for sound and experienced engineering judgment. The authors believe that by offering new and improved inspection technologies to experienced bridge engineers and inspectors, bridge inspection programs will be strengthened through enhanced inspection data and will be more objective, consistent, scientific, and efficient.
REFERENCES

2. Matsumoto et. al., Introduction of Non-Destructive Highway Inspection Methods using High Definition Video and Infrared Imaging Technology, The 34th IABSE Symposium, 2010.9
4. Florida Department of Transportation: Bridge Inspectors Field Guide Structural Elements, 2008
Pavement Management Analysis of Hamilton County, Tennessee USA, Using HDM-4 and HPMA

Main Author:
Trisha Sen
Engineer
Missouri Department of Transportation
sen.trisha1989@gmail.com

Co-Authors:
Mbakisya Onyango
Assistant Professor of Civil Engineering
University of Tennessee at Chattanooga
mbakisya_onyango@utc.edu

Joseph Owino
Associate Professor of Civil Engineering
University of Tennessee at Chattanooga
joseph-owino@utc.edu

Ignatius Fomunung
Associate Professor of Civil Engineering
University of Tennessee at Chattanooga
ignatius-fomunung@utc.edu

Jim Maxwell
Civil Engineer Manager II
Tennessee Department of Transportation
james.maxwell@tn.gov

Benjamin Byard
Tennessee Valley Authority
Dam Safety Governance
bebyard@tva.gov

ABSTRACT
According to the American Society of Civil Engineers Infrastructure Report Card issued in 2009, Tennessee roadways received a B- grade; primarily due to lack of sufficient funding and possibly lack of proper utilization of the available funds. Lack of sufficient funding for infrastructure management is an issue in many State Departments of Transportation in the United States. Pavement Management System (PMS) has demonstrated to be an essential tool for proper management of infrastructure and proper utilization of available funding. This study focused on determining the optimal utilization of available funds for Hamilton County in Tennessee, using PMS. Two software packages, Highway Development and Management System - version 4 (HDM-4) and Highway Pavement Management Application (HPMA), were used to assess the existing pavement conditions and predict future conditions; to determine the cost-effective maintenance treatment needed for a particular section; and finally to suggest the optimum utilization of funds.

PAVEMENT MANAGEMENT SYSTEM FOR CHATTANOOGA, TENNESSEE
The state of Tennessee has an average annual pavement maintenance budget of 60 million dollars for interstates and 120 million dollars for state routes. The actual need for pavement maintenance annually is 90 million dollars for interstates and 120 million dollars for state routes in...
the Tennessee Department of Transportation (TDOT) (6). Due to the difference in the actual amount required for interstates and the average amount received by TDOT, it is necessary to determine a methodology that properly allocates the available funding. This study utilized data from the City of Chattanooga, in Hamilton County Tennessee, to assess the cost-effective maintenance treatment as well as the proper distribution of funding.

The pavement management system (PMS) was used in this study as a tool to achieve prioritization of roadway maintenance. PMS is defined by the Federal Highway Administration as “a set of tools or methods that can assist decision-makers in finding cost-effective strategies for providing, evaluating, and maintaining pavements in a serviceable condition” (1). PMS is used to determine a process for reducing the timing between selecting a project and treatment application to ensure proper treatment application, maximize performance life and reduce overall life cycle cost of pavement sections. Two software packages HPMA and HDM-4 were used comparatively, as PMS tools to evaluate several objectives, such as present and future pavement condition, selecting the cost-effective maintenance treatment, and optimal usage of funding.

**Highway Development and Management System (HDM-4)**

Highway Development and Management System (HDM-4) is a computer software program developed by the World Bank to serve as a decision making tool for verifying the engineering and economic capability of investments in road projects. Project analysis allows assembling of several road networks or more than one road section together under one agreement. Project analysis provides the physical, functional and economic feasibility of specified project alternatives by comparing the alternatives to a “do-nothing” case. The major issues that the project analysis estimates are pavement structural performance, life cycle prediction of deterioration, maintenance effects and costs, road user costs and benefits, and economic comparison of project alternatives (2).

The program analysis deals primarily with the prioritization of a long list of candidate road projects into a one-year or multi-year work program under budget constraints. Program analysis deals with individual sections that are distinctive physical units distinguishable from the road network throughout the analysis. The program analysis examines the yearly maintenance program. Strategic analysis is performed on the entire road network for long term budget planning or for optimizing the maintenance strategies (HDM). In strategic analysis, the road system loses its individual

section characteristics by grouping all road segments with similar characteristics into the road network matrix categories (2).

For each case of project, program or strategic analysis, HDM-4 performs total life cycle conditions and costs for an analysis period under a user-specified set of conditions. The main set of costs for the life-cycle analysis comprises of the costs of capital investment, maintenance, vehicle operation, travel time, and accidents as an option. (3). Environmental effects, such as vehicle emissions and energy consumption, are calculated; however, they are not included in the cost streams. Optimal alternatives for each section are selected to maximize the economic benefits for the whole network while restricting the financial costs to less than the available budget (4).

**Highway Pavement Management Application (HPMA)**

Highway Pavement Management Application (HPMA) is a software program developed by Stantec Consulting that uses pavement condition data through a wide-ranging set of analysis models to determine current and future road and network condition. This software helps to define a set of Maintenance and Rehabilitation (M&R) needs of the network priorities and budget for the M&R treatments and development of the M&R program of projects (5).

HPMA is used to determine the total maintenance needs required. If these needs are dealt with immediately, this would reduce the needs in the future. The average performance trend based on pavement smoothness index (PSI), pavement distress index (PDI), and pavement quality index (PQI) for all sections are analyzed. This includes individual pavement sections deterioration curves under given maintenance options. The maintenance treatment required for each section and when the treatment needs to be applied are addressed by HPMA. The total cost required to take care of the total needs are also included.

The optimization analysis is performed using the available budget constraint. For this study, one million dollars were available for interstates and two million dollars for state routes in Hamilton County; both HDM-4 and HPMA used the same budget constraint.

**Input Data for HDM-4 and HPMA**

HDM-4 input data include the annual traffic growth rate, 1.8 %, vehicle and tire types, number of axles, average vehicle service life, and annual km driven, information on vehicle fleet (passenger cars, single unit, and tractor trailer), which is used to calculate vehicle operating cost and pavement performance. Other input data consists of pavement capacity, pavement type and characteristics, speed and speed reduction factors, pavement...
maintenance history, traffic counts and costs (unit, agency and user) (6). HPMA input data include pavement characteristics, surface distress severity, maintenance history, traffic data, and maintenance standard for intervention, unit cost and available budget.

**Parameters**
For both HDM-4 and HPMA parameters are provided that will classify the pavement condition and trigger maintenance requirement. In Table 1, the parameters for each category of roughness or ride quality in International Roughness Index (IRI) (in/mi) of a pavement are specified. The surface distress parameters include all structural cracking, wide structural cracking, transverse thermal cracking, number of potholes, raveling, and edge break. The mean rut depth is specified according to each condition (new, good, fair, poor, bad). The parameters for surface texture, which includes texture depth and skid resistance, are shown as well in Table 1. The parameters are used as failure criteria when using the HDM-4 software (6). These parameters and trigger values are used in the software packages for maintenance decisions.

### Table 1: Parameters (6)

<table>
<thead>
<tr>
<th>Roughness Parameters for Bituminous Pavement in IRI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Road Class</td>
</tr>
<tr>
<td>Bituminous (m/km) Primary</td>
</tr>
<tr>
<td>Bituminous (m/km) Secondary</td>
</tr>
<tr>
<td>Bituminous (m/km) Tertiary</td>
</tr>
<tr>
<td>Bituminous (in/mi) Primary</td>
</tr>
<tr>
<td>Bituminous (in/mi) Secondary</td>
</tr>
<tr>
<td>Bituminous (in/mi) Tertiary</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Surface Distress Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distress Mode</td>
</tr>
<tr>
<td>New</td>
</tr>
<tr>
<td>Good</td>
</tr>
<tr>
<td>Fair</td>
</tr>
<tr>
<td>Poor</td>
</tr>
<tr>
<td>Bad</td>
</tr>
</tbody>
</table>

### Rut Depth Parameters

#### Surface Texture Parameters

<table>
<thead>
<tr>
<th>Distress Mode</th>
<th>Mean rut depth (in)</th>
<th>Surface Texture</th>
<th>Texture Depth (in)</th>
<th>Skid Resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>New</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Good</td>
<td>0.079</td>
<td>2</td>
<td>Good</td>
<td>0.028</td>
</tr>
<tr>
<td>Fair</td>
<td>0.197</td>
<td>5</td>
<td>Fair</td>
<td>0.020</td>
</tr>
<tr>
<td>Poor</td>
<td>0.591</td>
<td>15</td>
<td>Slippery</td>
<td>0.012</td>
</tr>
<tr>
<td>Bad</td>
<td>0.984</td>
<td>25</td>
<td></td>
<td>NOTE: Skid Resistance is measured at 31 mph (50 km/h)</td>
</tr>
</tbody>
</table>
RESULTS

HDM-4

Vehicle fleets used in HDM-4 include passenger cars, two axle single unit trucks, and a tractor trailer (multi-axle trucks), with Annual Average Daily Traffic reflecting a 1.8% annual growth rate. Two road sections will be used to present results of the analysis. Two maintenance and rehabilitation strategies, overlay and micro surfacing, were used for the analysis. Figure 1 shows the average roughness in I-75, increases, but remains within “very good” region (IRI < 2.5) by year 2021, if either overlay or micro surfacing is applied. The roughness for SR 319, a secondary road, shows that if either overlay or micro-surfacing is applied, the road section will remain within “good” (IRI = 2.0 – 3.0) condition.

After running HDM-4, it was observed that the total damaged surface includes cracking, potholes, edge break, and raveling. Since defects take time to occur on pavements, in HDM-4, a defect will have an initiation phase (a time delay before a defect occurs), for example, the time before cracking occurs.

The intervention (2 < IRI ≤ 3) placed for both maintenance alternatives suggest that when roughness falls within this range, the maintenance alternative should be applied. This roughness constraint is placed by TDOT in order to prevent the increase in maintenance cost. Although, according to Table 1, this constraint is within good condition, the pavement sections are still maintained before the sections fall in poor condition. If the pavement roughness falls within the fair to poor range, the cost increases drastically. The cost would no longer be the cost of maintenance; now the cost of reconstruction might have to be considered.

The pavement condition for I-75 includes cracking percentages, rut depth, texture depth, and skid resistance. For I-75, a primary road, and SR 319, a secondary road, it is found that some defects occur before any maintenance (overlay or micro-surfacing) is applied but they are treated immediately because the roughness falls within the intervention range.

Based on the parameters described in Table 1, if the overlay alternative is applied in 2012, then the pavement will remain in good condition for the next ten years. For the micro surfacing alternative applied in 2012, I-75 seems to fall in the good condition region for skid resistance and texture depth based on Table 1 parameters. As for rut depth, the results indicate that it is within the good region but slowly reaches the fair region (5 mm) by year 2015. The structural cracking and roughness are predicted to remain in good condition for the next ten years (6).

The HDM-4 result for SR 319 compares an overlay and micro surfacing treatments. It was observed that the pavement condition prediction remains in a good condition for the ten year analysis period after an overlay application in year 2012. After the micro-surfacing application, SR 319 seems to fall in the good condition region for skid resistance and texture depth based on their acceptance levels. The skid resistance of 0.5 is in good range. As for rut depth, it is in good condition region (2 mm) in year 2012 but slowly reaches the fair region (5 mm) in year 2021. The structural cracking is predicted to remain in good condition until year 2021 (6).

Based on the pavement condition results, it can be concluded that micro-surfacing may cost less; however, this maintenance option does not necessarily improve all the distresses such as rut depth. Even though micro-surfacing is applied in 2012, signs of structural cracking and raveling appear the following year. On the other hand, using an overlay treatment improves the roadway section significantly where structural cracking and rut depth remains in good condition throughout the analysis period.

The multi-year optimization results produced using HDM-4 is shown in Table 2. The maximum Net Present Value (NPV)/cost is used to identify which section requires immediate maintenance attention. Using the budget constraint of one million dollars for interstates and two million dollar for state routes, the optimization results prioritizes each roadway section based on which section needs maintenance prior to other roadway sections. Based on Table 2, among the interstates, I-124 M 33 1 (3.2 km) requires immediate maintenance. The cost is also specified. The cumulative cost shown for each year expresses that the cost is within the budget constraint. The next section requiring maintenance would be I-124 P 33 1 (3.2 km) and then I-75 M 33 1 (2.4 km). As for the state routes, SR 29 P 33 1 (3.34 km) requires immediate maintenance.
TABLE 2: HDM-4 Optimization Results

| Year | Section   | Road Class       | Length (km) | Surface Class | AADT | Work Description | NPV/CAP | In millions |
|------|-----------|------------------|-------------|---------------|------|------------------|---------|
|      | I-124 M 33 1 | Primary or trunk | 3.2         | Bituminous    | 39500 | Overlay          | 84.263  | 0.23        |
|      | I-124 P 33 1 | Primary or trunk | 3.2         | Bituminous    | 39500 | Overlay          | 84.263  | 0.22        |
|      | I-75 M 33 1  | Primary or trunk | 2.4         | Bituminous    | 53865 | Overlay          | 76.668  | 0.25        |
|      | I-75 P 33 1  | Primary or trunk | 2.4         | Bituminous    | 53865 | Overlay          | 76.65   | 0.26        |
|      | I-24 P 33 1  | Primary or trunk | 0.5         | Bituminous    | 23615 | Overlay          | 23.417  | 0.03        |

| 2013 | I-124 M 33 1 | Primary or trunk | 3.2         | Bituminous    | 40211 | Overlay          | 84.263  | 0.23        |
|      | I-124 P 33 1 | Primary or trunk | 3.2         | Bituminous    | 40211 | Overlay          | 84.263  | 0.22        |
|      | I-75 M 33 1  | Primary or trunk | 2.4         | Bituminous    | 54834 | Overlay          | 76.668  | 0.25        |
|      | I-75 P 33 1  | Primary or trunk | 2.4         | Bituminous    | 54834 | Overlay          | 76.65   | 0.26        |
|      | I-24 P 33 1  | Primary or trunk | 0.5         | Bituminous    | 24040 | Overlay          | 23.417  | 0.03        |

| 2012 | SR 29 P 33 1 | Primary or trunk | 3.4         | Bituminous    | 71340 | Overlay          | 170.816 | 0.24        |
|      | SR 320 P 33 1| Secondary or main| 11.8        | Bituminous    | 27480 | Overlay          | 55.381  | 0.84        |
|      | SR 2 P 33 1  | Primary or trunk | 5.8         | Bituminous    | 28930 | Overlay          | 44.725  | 0.55        |
|      | SR 8 P 33 1  | Primary or trunk | 5.3         | Bituminous    | 22660 | Overlay          | 39.147  | 0.38        |

| 2013 | SR 29 P 33 1 | Primary or trunk | 3.4         | Bituminous    | 72624 | Overlay          | 170.816 | 0.24        |
|      | SR 320 P 33 1| Secondary or main| 11.8        | Bituminous    | 27974 | Overlay          | 55.381  | 0.84        |
|      | SR 2 P 33 1  | Primary or trunk | 5.8         | Bituminous    | 29450 | Overlay          | 44.725  | 0.55        |
|      | SR 8 P 33 1  | Primary or trunk | 5.3         | Bituminous    | 22660 | Overlay          | 39.147  | 0.38        |

**HPMA**

Reports in HPMA are given in terms PSI, PDI, and PQI. The IRI and rut depth data for each section are collected using an equipped vehicle with laser sensors, on sections that are defined to have a maximum length of one mile. TDOT uses several models such as distress index model, roughness index model, overall index model (PQI, PDI, PSI model) to predict distresses and roughness. If pavement resurfacing history information is available, then on a given stretch of road the first thing HPMA does is look at the last maintenance treatment type and predicts distresses using pavement deterioration models for both smoothness and distress. Then HPMA selects the anticipated measure and uses the respective index (PSI, PDI, and PQI), whichever is called for in the decision tree, to calculate a recommended treatment. If there is no site-specific information, HPMA uses default deterioration models.

Figure 2 shows the pavement performance using the PQI Index for the particular section of I-75. The section performance provides the deterioration curve for these particular sections. The average PQI for the particular year is specified. For instance, the average PQI for I-75 in 2012 is 3.37. The quality of the pavement deteriorates and as soon as it is approximately 2.5, the road section is maintained restoring it to about 4.0.

In 2012, an unconstrained budget of 91.8 million dollars is required to meet all the needs. If all sections (interstates and state routes) are treated in 2012, then the remaining sections expected in 2013 will only require 9.7 million dollars. However, if only some of the sections are treated, then the cost will be distributed in the upcoming years through an optimization analysis performed using the constraint budget of one million dollars for interstates and two million dollars for state routes.

Based on HPMA optimization results the maximum cost-effectiveness occurs for I-75 (0 - 1 mi); however, the PSI need year is 2021, so the specified maintenance treatment needs to be applied by 2021 (or the ninth year). This process continues where HPMA selects the next
maximum cost-effective ratio (I-124, 1 – 1.97 mi) and then finds that the PSI need year is 2016 and moves on to the next section. Among state routes, the maximum cost-effective ratio is found for SR 29 (1 – 2 mi); however, the PSI need year is 2015, so the maintenance should be applied by 2015 (or the third year). Then HPMA selects the next maximum cost-effective ratio (SR 320, 2 – 3 mi) and finds that the PSI need year is 2014 (second year), so this section is a priority in 2014.

The cost summary, shown in Table 3, includes the total cost acquired from the optimization results summarized according to maintenance activity and the year the activity needs to be applied.

<table>
<thead>
<tr>
<th>TABLE 3: Cost Summary for Treatment Required in Hamilton County</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Activity</strong></td>
</tr>
<tr>
<td>--------------</td>
</tr>
<tr>
<td>M1.2 Mill &amp; Replace 1”-2”</td>
</tr>
<tr>
<td>MO2400 MR 1-2” + OL 400 PSY</td>
</tr>
<tr>
<td>O200 Overlay &lt; 200 PSY</td>
</tr>
<tr>
<td>O400 Overlay 200-400 PSY</td>
</tr>
<tr>
<td>RECON Reconstruction</td>
</tr>
<tr>
<td><strong>Total Cost</strong></td>
</tr>
</tbody>
</table>

**CONCLUSION**

In assessing the existing pavements conditions and predict future conditions:

- With HDM-4, the pavement condition results for I-75 and SR 319, it can be concluded that micro surfacing costs less; however, this maintenance option does not necessarily improve all the distresses such as rutting.

- With HPMA the performance reaches a PQI < 2.5, the maintenance specified is applied and restores the section to the desired level.

- For determination of cost-effective type of treatment needed for a particular section and the suggested the optimum utilization of funds.

- With HDM-4, using the constraint budget, optimization analysis is performed and each roadway section is prioritized based on maximum NPV/cost. Among the interstates, I-124 M 33 1 (3.2 km) requires immediate maintenance. The next section would be I-124 P 33 1 (3.2 km) and then I-75 M 33 1 (2.4 km). As for the state routes, SR 29 P 33 1 (3.4 km) requires primary maintenance [Sen, 2013]

- With HPMA, using the constraint budget, each section is prioritized in order of maximum cost-effective ratio and also the PQI, PDI, and PSI trigger values is taken into consideration. If a section has high cost-effectiveness ratio, but the PQI, PDI, and PSI trigger values have not been reached, then that section may not require immediate attention and HPMA moves on to another section with the next largest cost-effective ratio.

It is recommended that HPMA cost-effective optimization analysis be used in order to adequately distribute the available funds.
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3D Laser Road Profiling for the Automated Survey of Road Surface Conditions and Geometry

Main Author:
John Laurent
Pavemetrics Systems Inc., Canada
jlaurent@pavemetrics.com

Co-Authors:
Yves Savard
Quebec Ministry of Transportation
yves.savard@mtq.gouv.qc.ca

Daniel Lefebvre
National Optics Institute of Canada
daniel.lefebvre@ino.ca

ABSTRACT
In order to maximize road maintenance funds and optimize the condition of road networks, pavement management systems need detailed and reliable data on the status of the road network. To date, reliable crack and raveling data has proven difficult and expensive to obtain. To solve this problem, over the last ten years Pavemetrics Inc. in collaboration with National Optics Institute of Canada and the Ministère des Transports du Québec (MTQ) have been developing and testing a new 3D technology called the LCMS Laser Crack Measurement System (LCMS). The LCMS system was tested on the network to evaluate the system’s performance at the task of automatic detection and classification of cracks. The system was compared to manual results over 9000 km and found to be 95% correct in the general classification of cracks. This paper describes results obtained recently regarding road tests and validation of this technology.

HARDWARE CONFIGURATION
The LCMS is composed of two high performance 3D laser profilers that are able to measure complete transverse road profiles with 1 mm resolution at highway speeds. The high resolution 2D and 3D data acquired by the LCMS is then processed using algorithms that were developed to automatically extract crack data including crack type (transverse, longitudinal, alligator) and severity. Also detected automatically are ruts (depth, type), macro-texture (digital sand patch) and raveling (loss of aggregates).

The sensors used with the LCMS system are 3D laser profilers that use high power laser line projectors, custom filters and a camera as the detector (1,2). The light strip is projected onto the pavement and the camera, as seen in Figure 1, captures the image. The shape of the pavement is acquired as the inspection vehicle travels along the road using a signal from an odometer to synchronize the sensor acquisition. All the images coming from the cameras are sent to the frame grabber to be digitized and then processed by the central processing unit. Saving the raw images would imply storing nearly 30 GB per kilometer at 100 km/h but using lossless data compression algorithms on the 3D data and fast JPEG compression on the intensity data brings the data rate down to a very manageable 20 Mb/s or 720 Mb/km. The critical specifications for the LCMS system can be found in Table 1.

FIGURE 1: LCMS on an Inspection Vehicle (Left), Laser Profiling of Cracks (Right)
The LCMS sensors simultaneously acquire both range and intensity profiles. Figure 2 illustrates how the various types of data collected by the LCMS system can be exploited to characterize many types of road features. The graph shows that the 3D data and intensity data serve different purposes. The intensity data is required for the detection of lane markings and sealed cracks whereas the 3D data is used for the detection of most of the other features.

### INTENSITY DATA

Intensity profiles provided by the LCMS are used to form a continuous image of the road surface. The first role of the intensity information is for the detection of road limits. This algorithm relies on the detection of the painted lines used as lane markings to determine the width and position of the road lane in order to compensate for driver wander. The lane position data is then used by the other detection algorithms to circumscribe the analysis within this region of interest in order to avoid surveying defects outside the lane. Highly reflective painted landmarks are much easier to detect in 2D since they generally appear highly contrasted in the intensity images. With the proper pattern recognition algorithms, various markings can be identified and surveyed. Figure 3 shows the results of the different types of images (intensity, range, and 3D merged image) that can be produced from the LCMS data.

### 3D RANGE DATA

The 3D data acquired by the LCMS system measures the distance from the sensor to the surface for every sampled point on the road. The darker the point, the lower the surface. In a range image the height can vary along the cross section of the road. The areas in the wheel path can be deeper than the sides and thus appear darker this would correspond to the presence of ruts. Height variations can also be observed in the longitudinal direction due to variations in longitudinal profiles of the road causing movements in the suspension of the vehicle holding the sensors. These large-scale height variations correspond to the low-spatial frequency content of the range information in the longitudinal direction. Most features that need to be detected are located in the high-spatial frequency portion of the range data. Figure 3 shows a 2 m (half lane) transverse profile where the general depression of the profile corresponds to the presence of a rut, the sharp drop in the center of the profile corresponds to a crack point and the height variations (in blue) around the red line correspond to the macro-texture of the road surface.

### MACROTTEXTURE

Macrotecture is important for several reasons, for example it can help estimate the tire/road friction level, water runoff and aquaplaning conditions and tire/road noise levels produced just to name a few. Macrotecture can be evaluated by applying the ASTM 1845-01 norm (3). This standard requires the calculation of the mean profile depth (MPD). To calculate the MPD, the profile is divided into small (10 cm) segments and for each segment a linear regression is performed on the data. The MPD is then computed as the difference between the highest point on the profile and the average fitted line for the considered portion. MPD is the only way possible to evaluate texture using standard single point (64 KHz) laser sensors. The LCMS however acquires sufficiently dense 3D data to not only measure standard MPD but also to evaluate texture using a digital model of the sand patch method (ASTM E965) (4). The digital sand patch model is calculated using the following proposed Road Porosity Index (RPI). The RPI index is defined as the volume of the voids in the road surface that would be occupied by the sand (from the sand patch method) divided by a surface area. The digital data can be obtained from the LCMS via a 3D laser profiler.
sand patch method implemented allows texture to be evaluated continuously over the complete road surface instead of measuring only a single point inside a wheel path. The RPI can be calculated over any user definable surface area but LCMS reports by default the macro-texture values within the 5 standard AASHTO bands. Results show that RPI measurements using the LCMS are highly repeatable as shown by road tests on several Alabama test sections and that RPI closely matches MPD measurements collected by standard texture lasers over a wide range of texture values.

RAVELING

Raveling is the wearing away of the pavement surface caused by the dislodging of aggregate particles and loss of asphalt binder that ultimately leads to a very rough and pitted surface with obvious loss of aggregates. In order to detect and quantify raveling conditions a Raveling Index (RI) indicator is proposed. The RI is calculated by measuring the volume of aggregate loss (holes due to missing aggregates) per unit of surface area (square meter). With the LCMS the high resolution of the 3D data allows for the detection of missing aggregates. Algorithms designed to specifically detect aggregate loss were developed in order to evaluate the RI index automatically.

CRACKING

Detecting cracks reliably is far more complex than applying a threshold on a range image. As mentioned previously the 3D profile data needs to be detrended from the effects of rutting and vehicle movements. Macrotexture is also a problem; road surfaces have very variable macrotexture from one section to the next and even from one side of the lane to the other. For example, on roads with weak macrotexture we can hope to detect very small cracks which will be harder to detect on more highly textured surfaces. It is thus necessary to evaluate and to adapt the processing operations based on the texture and type of road surface. Once the detection operation is performed, a binary image is obtained where the remaining active pixels are potential cracks. This binary image is then filtered to remove many of the false detections which are caused by asperities and other features in the road surface which are not cracks on the pavement. At this point in the processing, most of the remaining pixels can correctly be identified to existing cracks, however many of these crack segments need to be joined together to avoid multiple detections of the same crack. After the detection process, the next step consists in the characterization of the cracks. The severity level of a crack is determined by evaluating its width (opening) typically cracks will be separated in low, medium and high severity levels. The cracks also need to be grouped into two main categories: longitudinal and transverse. Furthermore, transverse cracks are further divided into complete and incomplete types and joints need to be classified separately. Longitudinal cracks are further refined into three sub-categories: simple, multiple and alligator.

The LCMS system was used by the MTQ to survey nearly 10,000 km of its road network. In order to validate the system, an independent 3rd party under the supervision of the MTQ was mandated to manually qualify the crack detection results of the LCMS system over the entire survey. To do this each 10 m section was visually analyzed and the results were categorized in three classes (good, average and bad). A forth class (not available (NA)) was used when for when it was not possible to correctly evaluate a section. Figure 4 shows an example of crack detection results on a 10 m pavement section. Transverse cracks are identified with a bounding box. Regions in red indicate high severity cracks (15 mm+) and light blue and green represent low severities (less than 5 mm). Table 2 shows the results of the compilation of the manual evaluation. The final results are deemed excellent by the MTQ as the overall ‘Good’ rating reaches 96.5%. Repeatability tests were also conducted on several MTQ test sections and the results demonstrate very repeatable crack detection results on the sections tested.

Figure 4: Example Crack Detection Results (Severity = Color Code)
### TABLE 2: 10,000 km Automatic vs Manual Survey Results

<table>
<thead>
<tr>
<th>District #</th>
<th>Total (10 m sections)</th>
<th>Results (manual classification)</th>
<th>Proportion (%)</th>
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<tr>
<td></td>
<td></td>
<td>Number of images (10 m sections)</td>
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<tr>
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<td></td>
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<tr>
<td>Total</td>
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<td>6732</td>
</tr>
</tbody>
</table>

### ROAD GEOMETRY

In order to measure road geometry (longitudinal profile IRI, slope and crossfall) with a very high degree of accuracy inertial measurement units (IMU) were added to the LCMS sensors. The IMU are composed of three axis accelerometers and gyroscopes where the vertical axis of the IMUs (gravity) is carefully aligned in the same plane as the lasers from the 3D sensors. This alignment allows for a direct referencing of the coordinate system of the IMU with the 3D sensors allowing the fusion of the data from both types of sensors.

Longitudinal profile is measured by integrating the vertical (G) accelerometer (z-axis) signal in order to measure the total vertical displacement of both the vehicle and the road profile while subtracting the distance variations between the vehicle and the road as measured directly by the 3D sensors. The 3D sensors thus allow the removal of the variations in the longitudinal profile that are caused by the vehicle suspension as the vehicle hits bumps in the road. The 3D sensors and the IMs must also be carefully synchronised for the whole process to work with precision.

After comparing the results obtained while measuring longitudinal profiles (IRI) on multiple runs at test sites in Utah by the LCMS versus another Class 1 profiler (Dynatest Mark IV - RSP), the tests and graphs show very comparable results in both accuracy and repeatability between the two systems.

Results and comparison tests using Proval software and Surpro reference profiles for evaluating ground truth show that the LCMS generates longitudinal profiles that match standard class 1 inertial profiler requirements. However the fact that the LCMS covers the entire 4 m width of a road lane allows the system to detect local IRI variations that can be missed by single point profilers. IRI maps of road surfaces demonstrate that surfaces are not uniform in IRI along both the transverse and longitudinal directions. Such IRI maps help identify local problems with the road surfaces that would be invisible to standard profilers thus improving upon existing profiling technology.

Slope and cross-slope is measured in a similar way as the longitudinal profile. In these cases however it is the signals coming from the IMU’s gyroscopes that are integrated in order to determine the pitch and roll of the vehicle. The 3D sensors are again used to measure the variations in the position of the vehicle versus the road to compensate for the pitch, roll and yaw of the vehicle as it sways over non-uniformities in the road and by accelerations caused by changes in vehicle speed.

### CONCLUSION

We have presented a road surveying system that is based on two high performance transverse 3D laser profilers that are placed at the rear of an inspection vehicle looking down in such a way as to scan the entire 4 m width of the road surface with 1 mm resolution. This configuration allows the direct measurement of many different types of surface defects by simultaneously acquiring high resolution 3D and intensity data. Examples of different algorithms and results were shown using the 3D data to detect cracks, ruts, evaluate macro-texture and to detect raveling while the intensity data was used for the detection of lane markings.

The LCMS system was tested at the network level (10,000 km) to evaluate the system’s performance at the task of automatic detection and classification of cracks. The system was evaluated to be over 95% correct in the general classification of cracks.

A Road Porosity Index (RPI) was proposed as a model to measure the equivalent of a digital sand patch. The digital sand patch (RPI) method implemented allows texture to
be evaluated continuously over the complete road surface and within each of the five AASHTO bands.

A Raveling Index (RI) indicator calculated by measuring the volume of aggregate loss (holes due to missing aggregates) per unit of surface area (square meter) was proposed. This indicator was shown to allow the quantification of the amount of raveling present and was shown to be highly repeatable.

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Improvement of Road Winter Maintenance Practices in Argentina

Authors:
Jorge Maturano
Coordinator, University Center for Winter Road Maintenance
National Bureau of Highways of Argentina
School of Mountain Roads Engineering
jmatur@eicam.unsj.edu.ar

Juan Marcet
Director, School of Mountain Roads Engineering
San Juan

Miguel M. Rivas
Chief, 4th National Bureau of Highways of Argentina District
Mendoza

Walter Perez
Coordinator, Corridor Nacional Route 7
Mendoza

ABSTRACT
This paper describes the development and improvement of winter maintenance practices in Argentina over the last decade, as a consequence of the leadership of the National Bureau of Highways of Argentina (DNV) and the United States Department of Transportation’s Federal Highway Administration (FHWA). In the early stages of the agreement, American winter maintenance experts at the Nevada Department of Transportation and University of Iowa produced an on site detailed and fundamental diagnosis on the state of winter maintenance practices in Argentina and offered guidelines for improvements. The University Center for Winter Road Maintenance (Centro Universitario de Vialidad Invernal (CUVI)) was created by the DNV at the School of Mountain Roads Engineering, (EICAM), a unit of the San Juan National University (UNSJ), and has proved a useful tool for sharing information to those who have planning and executive responsibilities in winter maintenance, as well as an effective device to coordinate training activities for the operators and technicians who perform related activities.

BACKGROUND
In 1932 the central government of Argentina approved Law 11658 creating the DNV as the responsible party for national roads and highways. Since creation, the Argentine road network progressively took shape based on three main principles: linking all regions and zones, building and maintaining effective access with large urban zones, and reliable connections with neighboring countries. Significant stretches of the network do not have year round reliable transit capability due to winter maintenance challenges. An analysis will be made on how to improve unreliable stretches stemming from the presence of snow and ice on the roads surface.

In Argentina the EICAM is working within the UNSJ and has been pursuing this challenge within its academic endeavors. With the support from DNV and the assistance rendered by American expertise since September 2000, the EICAM committed itself to study and analyze the affected road network areas to propose the best possible solutions in terms of both knowledge transfer and state-of-the-art technology applications.

In a combined effort with the DNV, Nevada Department of Transportation, and FHWA EICAM arranged for site visits by an expert team to assess the most critical locations of Argentina network experiencing winter road challenges. The locations of the on site visits consisted of the provinces of Mendoza, Neuquén, Santa Cruz and Tierra del Fuego. A report entitled Review on the Winter Road Maintenance Activities in Argentina was produced after the site visits providing detailed recommendations.
Recommendations from Review on the Winter Road Maintenance Activities in Argentina:

As the economic activity zones expand, their economic viability increasingly depends on the capability to sustain the unrestricted mobility of persons and freight throughout the year. Winter snowstorms, and the subsequent clearing tasks, deeply impact the ability to transport goods without restriction. Snowstorms that close roads for several days usually raise national awareness on the effectiveness of road clearance and preventive maintenance. In order to evaluate the state of winter road maintenance practices the DNV, EICAM, and FHWA experts teamed up into small groups who delved into the revision and observation of all aspects of snow clearing operations in affected areas of the road network to identify the actual problems and propose the most viable improvements.

The observations made by the teams are grounded on many years of field practice, as well as the fact that they are directly involved in the development of operational programs for winter road maintenance in the United States. There are several general categories into which the teams has grouped recommendations:

- Support activities
- Field survey and training
- Strategies and management
- Operational considerations

SUPPORT ACTIVITIES

Report Proposals

Development of an extensive training program for operators and engineers would be implemented. The content would be dependent upon the new methodologies, equipment, and fieldwork methods selected for application in real practice.

Creation of a professional center specialized on winter road maintenance would be addressed. The center would be in charge of developing technical literature and implementing design standards. It would also be aimed at becoming a referential point where professionals could find expert counseling and detailed information on a wide range of activities related to winter road maintenance. The University Center for Winter Road Maintenance was founded within the EICAM in 2005 through the DNV-UNSJ agreement.

Road deployed weather stations were used to provide the road maintenance crews and all roadway users with the most up to date weather information.

DNV Actions

After a seriously difficult economical period for both Argentina and the DNV, it was in 2005 that this institution signed the agreement with UNSJ to create the CUVI within the reaches of EICAM. The agreement was grounded on the objectives of fostering the development of the state of the art technologies for overcoming the hurdles posed by snow and ice.

Through an agreement signed with the Mendoza Regional Center for Scientific and Technological Research (CRICyT) CUVI began working on an all-inclusive system for the Corridor ‘National Road 7’, linking the city of Mendoza, Argentina and Santiago-Valparaiso, Chile. The DNV also undertook necessary action in preparing the necessary documents for procurement of winter road maintenance equipment.

FIELD SURVEY AND TRAINING

Report Proposal

A key factor for evaluating the recommendations was to plan a field trip to United States with a sizable group of road maintenance engineers in order to experience hands-on winter road maintenance practices. Only regions in the United States experiencing similar winter conditions were visited and evaluated.

DNV Actions

Under the coordination of the CUVI, the proposed field trips for survey and training were made in 2008. A group of professionals and technicians from the DNV and Provincial Department of Roads (Dirección Provincial de Vialidad (DPV)) visited the corresponding sites in the United States to acquire an academic training at the University of Iowa. Lectures were provided across the entire spectrum of subjects for winter road maintenance. Upon completion of classroom training at the University of Iowa the program continued on to various departments of transportation where field practice could be observed first hand. After returning home to Argentina the teams reported their own conclusions. They also developed a number of programs for applying these practices:

- Pilot projects
- Establish specific budget
- Incorporation of knowledgeable personnel
- Continuous training of personnel on all levels
- Inform involved authorities on benefits of winter road maintenance management system
STRATEGIES AND MANAGEMENT

Report Proposals
A well documented methodology was developed to evaluate new techniques and technologies along with the benefits they provide. Staff developed a training course in Spanish on winter road maintenance practices specifically tailored for local conditions. Regular meetings of engineering and maintenance personal were arranged to share operator experiences with new equipment and fieldwork practices.

DNV Actions
Training personal periodically held Workshop Journeys at various districts across Argentina in order to share experiences and discuss results. For example, at the VIIIº Technical Journeys workshop, DPV and DNV professionals and technicians invited Chilean counterparts who have similar experiences in winter maintenance practices. A series of training courses have been lectured in several districts as a means for transferring the acquired knowledge including snow fences, field equipment, avalanche risk, and environmental impacts.

A number of pilot projects were set forth with the assistance of American professionals including:

- Development and application of anti-icing means
- Adjusting existing equipment for anti-icing practices
- Development of snow fences
- Development of avalanche defense

Problems at Andean passes
In the Andean Cordillera, the mountainous border passes between Argentina and Chile are affected by substantial accumulations of snow and ice that hinder the free flow of users and goods. Winter road maintenance is to be performed so as to provide an adequate service level with minimal impact to the environment and reaching a sensible economy on resources employed.

At mountainous border passes and in provinces with roads experiencing similar snow and ice accumulation issues, task programs have included:

- Weather forecasting
- Use of anti-ice salts and brines (specific spreading equipment)
- Setting snow fences
- Building avalanche defenses

Agencies in United States, Canada, and several European countries have been working with snow melting solutions containing by-products from the food industry searching to find mixtures having greater viscosity allowing for a longer permanence of the melting chemical on the sprayed area. Some of the passes and road stretches used brine solutions and the addition of organic by-products from food industries (vinasse, stillage) from sugar cane, beets, grapes and other sources. This effect leads to a reduction of brine and salt applications lowering costs and reducing pollution consequences.

Snow fences and weather stations have been installed in multiple locations while work commenced on passive defenses against avalanches. Studies are currently under way to apply active systems. Techniques are already in place along the access road to the mining project Veladero in the province of San Juan, with equipment that features a number of GasEx Cannons.

OPERATIONAL CONSIDERATIONS

Report Proposal
Teams established a testing program aimed at determining the effectiveness of ice-melting chemicals. They also developed clear design standards for improving the safety levels when treating the lateral zones of the roadway, with the inclusion of, but not limited to safety fences, railings and reflective poles.

A snow control program was established including technical approaches for machine piling snow and snow storage, approaches for controlling snowfields (ventisqueros), snowdrift runoff, and both natural-occurring and man made snow barriers. An analysis on how the ground and relief along the road can affect the snow accumulation on the road surface was also performed.

Teams will also provide an in-depth avalanche risk assessment and a thorough analysis of the methodology to face such hazards using both active and passive approaches.

DNV Actions
An agreement signed with the CRICyT in 2006 commissioned the development of a management system for Route 7 that connects Argentina and Chile through Los Libertadores Pass. This project is already at the setup
and testing stages and is intended for managing the corridor from the city of Mendoza to the international border. An operations control unit was installed in Uspallata.

OTHER DEVELOPMENTS

Different developments were carried out in various DNV districts in order to use their equipment with anti-ice mixtures. Highlights the districts are noted below:

Mendoza
- Automated solutions mixing plant
- Built plant to elaborate solutions
- Retrofitted dumping trucks to work with solutions
- Attached grader-type blades for clearing snow
- Installed snow fences
- Installed passive defense for avalanche control
- Collaborated with municipal administration of Malargüe to apply anti-ice solutions on main urban roads

Neuquén
- Built a plant for elaborating anti-ice solutions
- Retrofitted dumping trucks to work with solutions
- Attached grader-type blades for clearing snow
- Installed snow fences

Santa Cruz
- Built plant for elaborating anti-ice solution mixtures
- Retrofitted dumping trucks to work with solutions
- Attached grader-type blades for clearing snow
- Installed snow fences
- Installed weather stations
- Upgraded control center

T. del Fuego
- Building plant for elaborating solutions mixtures
- Retrofitted dumping trucks to work with solutions
- Attached grader-type blades for clearing snow

EVALUATION AND FURTHER INVESTIGATION

The results have all met all expectations and provided significant savings. Benefits have been realized in terms of reduced work schedule for personnel, reduced wear and fuel consumption on equipment, and specifically a lower ratio of snow and ice melting chemicals.

These achievements have made the problems of the main pass (Los Libertadores) between Argentina and Chile focused on the international agreements and the customs-sanitary controls. The border pass has a high traffic rate of large trucks of about 1200-1500 large-size rigs per day. Route 7 starts at the city of Buenos Aires then traverses Argentina westward to Mendoza and its Paso Los Libertadores at Cristo Redentor Bi-national Tunnel, connecting with Route 60 in Chile and leading to either Valparaiso or Santiago de Chile. The corridor is also used for truck transportation by southern Brazil, Paraguay and Uruguay.

With the experience gained from other countries, the EICAM is undertaking its own research projects in a joint-collaboration with the Biotechnology Institute of the UNSJ. The research is focused on developing mixtures of snow and ice melting chemicals as well as organic byproducts using local grown materials. A parallel project is developing simple but practical equipment for metering the saline residues left on the road surface in a joint venture with the Automatics Institute INAUT of the UNSJ. The organic byproducts were chosen primarily from the local crops with special attention given to residual products from the industrialization of grapes, sugar cane, beets, pears and other items similar in nature.

The developed mixtures were brine + organic byproduct, with percentage of the latter matter ranging from 5 to 20%, and also brine (80%) + calcium chlorine (10%) + organic byproduct (10%). Given the product costs and availability rates, local agencies have opted for using commercial vinasse due to the lower costs as compared to the other byproducts. By adding vinasse to the solution the longevity of the chemicals is up to five times that of applications of only brines. With the application of this mixture types at critical road spots, which are thoroughly known by the maintenance personnel, and working on a basis of weather forecast reports, it has been possible to significantly decrease the snow event road closure periods of the international highway.
Predicting Deterioration for the Saudi Secondary Urban Road Network

Author:
Muhammad Mubaraki
Department of Civil Engineering
College of Engineering
The University of Jazan, Saudi Arabia
mmubaraki@jazanu.edu.sa

Co-Author:
HossamAl-Din Sallam
Department of Civil Engineering
College of Engineering
The University of Jazan, Saudi Arabia
hossam_sallam@yahoo.com

ABSTRACT
The development of deterioration prediction models for secondary urban road across Saudi Arabia is investigated. The developed models are based on pavement condition data maintained by the three municipalities of Riyadh city, Jeddah city, and Dammam city. Models are available for the most common pavement distress types on secondary roads. They are block cracks, longitudinal and transverse cracking, patching, potholes, depressions, and weathering and raveling. In all prediction models, age is by far the most significant predictor of deterioration. The traffic volume in terms of Annual Daily Traffic (ADT) and the drainage play only a secondary role in forecasting prediction of distress propagation. In general, the developed models provided an adequate fit and generated predictions that conform to accepted engineering judgment.

BACKGROUND
The main element of the highway system is the pavement. The pavement represents one-half of total highway expenditure and moreover expenditures on pavements continue to grow as maintenance and rehabilitation are required (1). Transportation infrastructure plays a vital role in the economic, social, and state of all countries and this role cannot be neglected. Models of road deterioration help to improve management, planning techniques, and give economic justification of expenditure and standards in the highways sector. Pavement condition prediction models can be developed to forecast condition in terms of one of the several different measures of condition. Sometimes models are classified based on what types of parameters they predict. Four common groupings include: Primary response, structural performance, functional performance, and damage (2).

Darter outlined basic requirements for a reliable prediction models as:

- An adequate database based on in-service sections
- Consideration of all factors that affect prediction or performance
- Selection of an appropriate functional form of the model
- A method to assess the precision and accuracy of the model (3)

The prediction models predict pavement rate of deterioration as a function of the factors that affect pavement condition (1). However, most of the previous works depended on developing a combined index for pavement evaluation purposes (4). Pavement surface distress is a major concern associated with pavement life and driving quality. Therefore, it is recommended that for long term planning each organization collect sufficient data to model the behaviour of each distress types. In addition, studying each distress type individually will help investigate the correlation between the different distresses (5).

RESEARCH SCOPE
The following points were made to clarify the proposed methodology for this paper. To obtain generic models that can be utilized with a significant level of confidence,
this study has covered all possible and accessible pavement sections that satisfy the research scope. The pavement management systems (PMS) unit at Riyadh region, Jeddah, and Dammam municipalities are the source for the data. In this study, the data have been checked for outlier cases.

The dataset was developed through different steps as follows:

- Some apparent outliers exist within the data but all data was analysed so that extreme values could be identified as part of modelling process
- Only overlaid sections were included in the study to ensure that the initial pavement condition index is close to 100
- Any section that had been merged with another due to any reason was removed to ensure accuracy for the selected sections used in building the research dataset
- Maintenance ratio was also checked to ensure that most of the section had been maintained by overlay. Any section with less than 90% was removed. The maintenance ratio is calculated based on the maintained areas and the surveyed areas for a given section
- Any section was exposed to maintenance activities after the overlay date were removed
- Any section satisfies the above four conditions was used to build the research work or the dataset for the research and can be considered as the original work in this study
- Each section contains different number of sample unit depends on the geometry of the section. For example, some sections have dimension of 100 meter in length and 3 meter in width, some have dimension of 200X3, and 300X3
- Each sample unit contains one or more than pavement distress type’s record (type, severity, density)

EXPERIMENTAL DESIGN FOR SECONDARY ROADS

Data was collected for eleven years for secondary roads to be used in building a database. A specific database was developed for this study in a systematic and coherent way that included information on pavement characteristics, pavement distress data, and pavement maintenance data. Pavement characteristics data included information on pavement class, pavement type, pavement age, traffic volume, and availability of a drainage system. Pavement distress data included information on distress type, severity, extent and location. Pavement maintenance data included information about what type of maintenance strategy has been applied on the pavements and the maintenance date. However, experiment design is a discipline that has very broad application across all the sciences. A total of 228 secondary overlaid pavement sections were found to be applicable for the study constraints. The independent variables are pavement age, and availability of drainage system. In total 641 observations on all selected pavement sections for each distress type (the dependent variable) were used to study the significant factors, of which 78 observations for old sections, 143 observations for moderate sections, and 420 observations for young sections (newly paved). On other hand 202 observations for sections with drainage system, and 439 observations for sections without drainage system.

The dependent variables are the most common distress on the secondary roads are shown in Table 1.

<table>
<thead>
<tr>
<th>Distress Names (the dependent variable)</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Block Cracks</td>
<td>D2</td>
</tr>
<tr>
<td>Longitudinal &amp; Transverse Cracking</td>
<td>D3</td>
</tr>
<tr>
<td>Patching</td>
<td>D4</td>
</tr>
<tr>
<td>Potholes</td>
<td>D5</td>
</tr>
<tr>
<td>Depression</td>
<td>D6</td>
</tr>
<tr>
<td>Weathering and Ravelling</td>
<td>D11</td>
</tr>
</tbody>
</table>

The units are unit less because density measures the amount of distress dividing by sample area as follows:

Density for distress types measured by the square meter, by the linear meter, or by number like potholes (D5) are calculated as follows;

Density for distress D2, D3, D4, D5, D6, and D11 is measured by the following formula:

\[
\text{Density} = \frac{\text{Distress amount in square meters}}{\text{Sample unit area in square meters}} \times 100
\]

NONLINEAR REGRESSION MODELLING

Background

From an engineering point of view, the pavement deteriorates in a particular pattern. Put simply, the conditions that must be met by prediction models, which will limit the form to those appropriate for the modelling process, may be summarized as follows:
• The initial value of all damage is zero
• Most damage has a slope that is initially zero. However, some damage types such as roughness or rutting have an initial upsurge
• Most damage is irreversible; the slope must always show a worsening of condition unless a treatment is applied
• Damage functions such as the distresses under study have final slope zero, damage reaches the horizontal line at 100%. By contrast, other types of damage such as roughness or rutting don’t have this constraint
• The minimum value for damage should not be negative at any value of the pavement age
• The maximum value of damage has an upper limit only for those types of distresses for which the final slope is zero

In the light of the literature review and different types of modelling techniques, it is clear that the pure mechanistic models, the mechanistic–empirical models, and the subjective probabilistic models are not relevant to the available data, which depends on a surface distress survey only (6,7,8). The empirical technique (regression Models) is very suitable for the situation of this study. It is practical, simple, and easy to develop provided that adequate data are available (9).

**Distress Prediction Equations**

Nonlinear regression models, divided into families according to their typical behaviour, were tested and evaluated. These were exponential models, power models, yield density models, growth models, sigmoid models, and miscellaneous models. (10,11). The evaluation was based on the boundary conditions and the form of equations that provide the best fit to the actual data. The sigmoid model family was selected to fit the data because it is the one that can suit the research methodology and fits the boundary conditions. Various scientists and researchers discovered, reinvented, and adapted the curves of nonlinear S-shape many times for different domains of knowledge. Therefore, S-shaped curves possess a lot of different names: Logistic curve, Verhulst-Pearl equation, Pearl curve, Richard’s curve (Generalized Logistic), Growth curve, Gompertz curve, S-curve, S-shaped pattern, Saturation curve, Sigmoid curve, Foster’s curve, Bass model, and many others (12, 13).

Several equations of sigmoid form appear to fit the data with more or less the same coefficients. The criterion that dictated the selection of a particular function for each distress was its ability to satisfy the initial and possibly the end of life boundary conditions. The evidence from the literature has indicated the suitability of sigmoid functions to represent distress predictions (14, 15, and 16). As result of that, the study performed one form for each distress model for uniformity and general flexibility and also for calibration.

A simple S-curve can be defined in simple form such as:

\[ y = a \left[ 1 + e^{-\frac{t^b}{c+t^b}} \right] \]  

(1)

Where a, b, and c are constant values that define the shape of the sigmoid

The logistic function or logistic curve is the most common sigmoid. This function finds application in a range of fields including engineering, and others. However, it is sufficient to compute t over a small range of real numbers. The simple logistic function can be defined by the formula.

\[ y = \frac{1}{1 + e^{-t}} \]  

(2)

The logistic distribution is a continuous probability distribution. Its cumulative distribution function is the logistic function. This formula can be defined in such format as follows

\[ y = \frac{a}{1 + e^{-(t-m)/s}} + d \]  

(3)

*Where*

- a = Parameter controls the upper asymptote
- m = Parameter controls the time of maximum growth
- s = Parameter controls the growth rate
- d = Parameter allows the representation of a lower asymptote in a similar manner in the generalised form
- t = Parameter is the time

The generalized logistic curve or function, also known as the Richard curve is a widely used and flexible sigmoid function for growth modelling, extending the well-known logistic curve as following:

\[ y(t) = a + \frac{b - a}{1 + \lambda e^{-\beta \frac{(t-m)\gamma}{s}}} \]  

(4)
Where
a = lower asymptote
b = upper asymptote, if a=0 then b is called the carrying capacity
= growth factor
= affects near which asymptote maximum growth occurs
= depends on the value y (t)
t = time
m = time of maximum growth if =

However, the standard equation of the generalized curve is symmetric in shape around a mid-point. This equation has been used in predictive relationships for pavement design since the early 1980s (17). The standard one has this formula

\[ y(t) = a + \frac{b}{1 + e^{-\beta + \delta(x-m)}} \]  
(5)

However, this can be modified to this form

\[ y = a + \frac{b}{1 + \lambda e^{-\beta(x-m) / x}} \]  
(6)

Where
a = Parameter controls the lower asymptote
b = Parameter controls the upper asymptote
\( \beta \) = Parameter controls the growth rate
m = Parameter controls the time of maximum growth
\( \lambda \) = Parameter controls where maximum growth occurs
x = Parameter is the time

Another example of a sigmoid curve that reaches at large values is the Gompertz curve. It is a type of mathematical model for a time series, where the growth is slowest at the start and end of a time period. The curve has the following form:

\[ y = ae^{be^{ct}} \]  
(7)

Where
a = Upper asymptote
c = Growth rate
b, c = Negative numbers

Weibull equations haven been used in the representation of sigmoid functions. For example the cumulative distribution function for Weibull is in the form of

\[ y(t) = 1 - \exp\left(-\frac{t}{\beta}\right)\omega \]  
(8)

The modification of the above equation leads to an equation in this form:

\[ y(t) = \frac{a}{e^{(\beta / t)^{\omega}}} \]  
(9)

Where
\( \alpha \) = Asymptote that controls upper limit= 100
\( \beta \) = Position of the first inflection point on the curve
\( \omega \) = Coefficient that controls the shape on the curve

A similar equation with more parameters has been used by Texas Department of Transportation (14, 18).
The Stannard and Shuute equations (19) are sigmoid functions that measure the growth rate. They have a complex structure and more than 3 parameters in the form. They are written respectively as the follows:

\[ y(t) = a\{1 + \exp[-\frac{1 + ktb}{p}]\}^{-p} \]  
(10)

\[ y(t) = \{ya^2 + (2ya^2 - ya^b)\frac{1-\exp[-a(t-\lambda)]}{1-\exp[-a(\lambda-\lambda_1)]}\}^{1/b} \]  
(11)

The Morgan-Mercer-Flodin model has the following formula (13)

\[ y = a - \frac{a - \beta}{1 + \lambda t^{\alpha}} \]  
(12)

\( a \) = Parameter controls the upper asymptote
\( \beta \) = Parameter at t=0,
\( \lambda \) = Parameter controls the growth rate
\( \alpha \) = Parameter controls the point of inflection

The Choice of Sigmoid Function
The choice of function among a number of useful and applicable functions can be considered in terms of qualitative considerations like the appearance of forecast plots, intuitive reasonableness of the model, simplicity of the form model, and ease of use. The idea of qualitative considerations is to minimize the number of functions to a reasonable number for further comparisons. At first, therefore, these models were compared with respect to their ease of use. It is very obvious that equations 4, 5, 6, 10, 11, and 12 have complex structure and more than three parameters. Therefore, these six equations will be excluded from the final comparison.
The simple logistic function, equation 2, is sufficient to compute t over only a small range of real numbers and
it does not start at zero. The Gompertz curve, equation 7, reaches at large values but it does not start at zero. Therefore, equations 2 and 7 will also be discarded because they violate one of the boundary conditions which is the initial value of all damage is zero. Weibull curve, equation 8, is going to be neglected.

After careful consideration and for ease of use and ability to fit the data, three equations out of the twelve options were selected to do the modelling and to explore the difference between them in order to select the best one. The equations are number 1, 3, and 9. However, a single form in the modelling process must be used as will be discussed in the rest of this paper.

Selecting the Best Form
All the three equations are useful in modelling pavement prediction based on research methodology, boundary condition, available data, and the engineering principle for this research. However, a single form must be selected to implement it for modelling. The most popular criteria for comparing different models are standard error of the model mean square of error (MSE) and coefficient of determination of the model R2. However, for nonlinear analysis, R2 is not always reliable a parameter to measure the goodness of fit as for linear regression analysis (20). Therefore at this stage only MSE would be calculated to judge which one is the best among the three and consequently it would be selected to be the proposed model form for the urban main roads data as shown in Table 2.

<table>
<thead>
<tr>
<th>Distress Code</th>
<th>Comparison Between Selected Models</th>
<th>Standard Error of Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Equation (1)</td>
<td>Equation (3)</td>
</tr>
<tr>
<td>Block Cracks</td>
<td>5.97</td>
<td>6.15</td>
</tr>
<tr>
<td>Longitudinal &amp; Transverse Cracking</td>
<td>5.74</td>
<td>5.27</td>
</tr>
<tr>
<td>Patching</td>
<td>8.95</td>
<td>9.33</td>
</tr>
<tr>
<td>Potholes</td>
<td>3.91</td>
<td>4.29</td>
</tr>
<tr>
<td>Depressions</td>
<td>6.95</td>
<td>6.91</td>
</tr>
<tr>
<td>Weathering &amp; Ravelling</td>
<td>5.69</td>
<td>5.53</td>
</tr>
</tbody>
</table>

It can be concluded that equation 9 records the lowest values of standard error in most cases. Therefore, the proposed distress equation of the model will in the form of equation 9.

The form has only one predictor variable, which is the pavement age time t. The form has one known parameter to control the upper limit to not exceed one hundred and it has zero intercept because damage has a slope that is initially zero as discussed in the boundary conditions. The form has two unknown parameters \( \beta \) and \( \omega \) to build the shape characteristics of a prediction model for each pavement distress type.

Method of Calculating Shape Coefficients
The nonlinear regression procedure in the SPSS software package (21) was used to calculate coefficients for the proposed sigmoid function for each distress type. The nonlinear regression procedure allows for the specification of any equation form, any number of dependent variables and the ranges in which the dependent variables are expected to fall. Table 3 summarises the calculated shape coefficients for the distress prediction models. The proposed form has one predictor variable, which is the pavement age.

<table>
<thead>
<tr>
<th>Distress Code</th>
<th>Model Shape Coefficients</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \beta )</td>
</tr>
<tr>
<td>Block Cracks</td>
<td>27.768</td>
</tr>
<tr>
<td>Longitudinal &amp; Transverse Cracking</td>
<td>31.830</td>
</tr>
<tr>
<td>Patching</td>
<td>14.179</td>
</tr>
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<td>Potholes</td>
<td>33.543</td>
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<tr>
<td>Depressions</td>
<td>30.407</td>
</tr>
<tr>
<td>Weathering &amp; Ravelling</td>
<td>47.375</td>
</tr>
</tbody>
</table>

Calibration Methodology
As discussed and concluded earlier, the pavement age is the only factor that shows significance in the prediction modelling. If we consider the other two-predictor variables, which are the traffic and the drainage, the proposed distress equation would have been in the following form:

\[
\begin{align*}
\alpha &= \text{Asymptote that controls the upper limit} = 100, \\
\beta &= \text{Position of the first inflection point on the curve}, \\
\omega &= \text{Coefficient that controls the shape on the curve}, \\
\chi &= \text{Modifying coefficient for traffic}, \\
\delta &= \text{Modifying coefficient for drainage}.
\end{align*}
\]

The purpose of the traffic and drainage coefficients specified in the proposed distress model is to modify the distress equation to be as accurate as possible provided the data are available. In the following subsections, the modifying coefficients for traffic and for drainage are investigated to be included in the model or not.
Assessing the Selected Models

Measures of adequacy are very important before adopting a model and implementing it in a pavement management system (22, 23). In any nonlinear analysis, it is necessary to assess the fit of the model to the data and to assess the appropriateness of the assumptions about the regression analysis (25), namely: residual analysis, non-variance constant, non-independence of the error variable, and non-normality.

Models Adaption

Once a proposed model gives a good description of the process being identified, and the assessed results appear reasonable as discussed earlier, the time has come to adopt it. However, the proposed model gives the predicted values only. It is not enough to know the best-fit values for the model. How precisely the best fit values of the parameters are also important. Therefore, confidence interval should be investigated to get a good sense about the prediction.

The nonlinear regression results can be interpreted only if the assumptions of nonlinear regression are true or at least not badly violated (25, 26). Confidence intervals give a sense of whether results are any good. If the confidence intervals are narrow, this indicates that the parameters are precise. Whereas if the confidence intervals are very wide, this indicates that parameters are not precisely determined. There are many methods where the confidence interval can be calculated.

The Developed Models

Six models have been developed for urban secondary pavement distress models using the modified function equation 9. The models are: block cracking model, longitudinal & transverse mode, patching model, potholes model, depressions model, and weathering & ravelling model. Figures 1a to 5f show the distress prediction models for each flexible pavement distress. Five curves are plotted. The first and the foremost is the solid line, which is the predicted model for a distress type. The second and the third curves are the 95% upper and lower confidence limits of the predicted values from the model. These curves were developed by generating a confidence region based on the upper and lower limits of the estimated parameters of the model. The fourth and the fifth curves are the 95% upper and lower confidence intervals of the measured data. These curves were developed by the asymptotic method.

FIGURE 1: Six models for urban secondary pavement distress models as follows:

- Block Cracking Model
  \[ 100 = e^{(27.768/1)0.598} \]
- Longitudinal & Transverses Cracking Model
  \[ 100 = e^{(31.830/1)0.491} \]
- Patching Model
  \[ 100 = e^{(14.179/1)0.415} \]
- Potholes Model
  \[ 100 = e^{(33.543/1)0.608} \]
- Depressions Model
  \[ 100 = e^{(30.407/1)0.749} \]
- Weathering & Ravelling Model
  \[ 100 = e^{(47.375/1)0.328} \]

CONCLUSION

In this study, historical data of distress on the urban secondary roads network of three largest municipalities cross Saudi Arabia have been employed in modelling the S-shape for each individual flexible pavement distress type under imposed boundary conditions. As formulated, age is a surrogate for traffic and drainage. The developed models could provide a reasonable prediction of pavement condition. The models were assessed by standard error of estimate and coefficients of determination. It would be interesting to determine whether these models are applicable for other cities out of Saudi Arabia. If so, these models can be applied in PMS implementation by highway authorities for flexible pavements.
REFERENCES


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* Denotes Ex-Officio Member
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