No Boundaries
Roadway Maintenance Collaboration

Papers Related to Maintenance from the
2017 TRB Annual Meeting

Contents

This is a compendium of maintenance-related papers from the 2017 Transportation Research Board Annual Meeting as prepared by the No Boundaries pooled fund project (#TPF-5(330)).

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Asset Management

Application of Causal Loops Diagrams to Model Improvement Costs for Highway Bridge Inventories
Paper number 17-00124, http://amonline.trb.org/63532-trb-1.3393340/t003-1.3409998/737-1.3410081/17-00124-1.3402897/17-00124-1.3410086

Authors:
   Srimaruthi Jonnalagadda, Clemson University, srimarj@clemson.edu
   Brandon E. Ross, Clemson University

Abstract: The quality of bridge infrastructure is affected by a variety of factors. Traffic and aging deteriorate bridges; maintenance and repair operations mitigate deterioration. The overall quality of a bridge inventory is also affected by new construction, and through removal or improvement of poor bridges. This study uses tools from the field of systems dynamics to study changes to the quality of bridge inventories. A causal loop diagram (CLD) is developed to qualitatively describe the relationships and actions impacting the quality and improvement costs of a bridge inventory. Relationships expressed in the CLD consider physical, economic, and policy factors. A quantitative model is also developed, which

is based on a portion of the CLD. Using South Carolina as a test subject, the model is used to calculate the inventory-level improvement costs as a function of annual improvement budget. Data from the National Bridge Inventory are used to develop the model. This paper is presented as a first step towards the use of system-based approaches to study highway bridge inventories. Recommendations are given for extending the proposed CLD and quantitative model.

Bayesian Detection of Unrecorded Maintenance and Rehabilitation Treatments in Pavement Management

Authors:
    Lu Gao, University of Houston, lgao5@central.uh.edu
    Shi Giu, Beijing University of Technology
    Tejus Renuka Prasad, University of Houston

Abstract: Pavement maintenance and rehabilitation (M&R) records are important because they provide documentation that M&R treatment is being performed and completed appropriately. Moreover, the development of pavement performance models relies heavily on the quality of the collected condition data and M&R records. However, the history of pavement M&R activities is often missing or unavailable to highway agencies due to various reasons. Without accurate M&R records, it is difficult to determine if a condition change between two consecutive inspections is the result of M&R intervention, deterioration, or measurement errors. Also, the time gaps between condition inspections are usually unevenly spaced, which adds more complexity to data analysis. In this research, a Bayesian model was proposed to detect if an M&R treatment was applied to a pavement section between two consecutive condition inspections. The proposed model was demonstrated using data from the Long Term Pavement Performance (LTPP) database and high accuracy was obtained.

Comparison of Life Cycle Assessment Tools for Road Pavement Infrastrucutre

Authors:
    João Miguel Oliveira dos Santos, IFSTTAR, AME-EASE
    Senthilmurugan Thyagarajan, Turner Fairbank Highway Research Center,
        senthil.thyagarajan.ctr@dot.gov
    Elisabeth Keijzer, TNO
    Rocío Fernández Flores, ACCIONA S.A.
    Gerardo Flintsch, Virginia Tech Transportation Institute

Abstract: Road pavements have considerable environmental burdens associated with their initial construction, maintenance, and usage, which has led the pavement stakeholder community to congregate efforts to better understand and mitigate these negative effects. Life cycle assessment (LCA) is a versatile methodology to quantify the effect of decisions regarding the selection of resources and processes. However, there is a considerable variety of tools for conducting pavement LCA. The objective of this paper is to provide the pavement stakeholder community with insights on the potential differences in the life cycle impact assessment results of a pavement by applying American and European LCA tools, namely PaLATE V2.2, VTTI/UC asphalt pavement LCA model, GaBi, DuboCalc, and ECORCE-M, to a Spanish pavement reconstruction project. Construction and maintenance life cycle

stages were considered in the comparison. Based on the impact assessment methods adopted by the different tools, the following indicators and impact categories were analyzed: energy consumption, climate change, acidification, eutrophication, and photochemical ozone creation. The results of the case study showed that it is of crucial importance to develop (1) a standardized framework for performing a road pavement LCA that can be adapted to various tools and (2) local databases of materials and processes that follow national and international standards.

A Comprehensive Review of Approaches Used by Ontario Municipalities to Develop Road Asset Management Plans

Paper number 17-00281, http://amonline.trb.org/63532-trb-1.3393340/t001-1.3410589/275-1.3410696/17-00281-1.3400248/17-00281-1.3410710

Authors:
    Tamer E. El-Diraby, University of Toronto
    Sherif Kinawy, University of Toronto
    S. Madeh Piryonesi, University of Toronto, madeh.piryonesi@mail.utoronto.ca

Abstract: Municipal asset management gained momentum in Canada over the past two decades. Ontario provincial government has tied provincial funding to development of asset management plans. Accordingly, all municipalities are required to develop a detailed asset management plan to facilitate access to provincial funding. Nonetheless, asset management knowledge is nacent in Ontario. Considerable variances are discernable in asset management plans in the wake of various aptitudes of municipalities as well as lack of a standardized template. Hence, analyzing these plans could be highly rewarding and the results could be used for identifying needs of municipalities and exposing gaps in provincial support programs. In this paper a comprehensive study is conducted on current infrastructure asset management plans in Ontario with emphasis on the road sector. A sample of 24 municipalities was selected for this study. Careful consideration was given to choosing rural and urban municipalities with different sizes, from different areas of the province and with different experiences in asset management. Moreover, some interviews were conducted to elicit a deeper understanding of the tools and methods used by the municipalities. The aim of this study is discerning the defects in the status quo of the asset management plans and setting future targets. For this purpose. the plans were analyzed and rated from different perspectives (e.g. structure, data collection methods, deterioration modeling and cost estimation). The differences and similarities among the employed decision-support tools were highlighted. The majority of studied municipalities, especially small ones, have serious issues in data collection, data management and defining and meeting level of service. Lack of reliable data and proper deterioration models made municipalities decide based on rough analyses or anecdotal evidences. Furthurmore, the authors discovered that one of the most challenging issues for the success of asset management in Ontario is lack of adequately trained human resources. After discussing the main issues, a number of recommendations are made to enhance the different components of the asset management plans.

Cost-Effective Performance Management for Washington State Pavement Assets

Paper number 17-02807, http://amonline.trb.org/63532-trb-1.3393340/t025-1.3403719/711-1.3403928/17-02807-1.3399561/17-02807-1.3403931

Authors:
    Jianhua Li, Washington State Department of Transportation, lijia@wsdot.wa.gov
    David R. Luhr, Washington State Department of Transportation
    Mark Russell, Washington State Department of Transportation
    Tim Rydholm, Washington State Department of Transportation
    Jeff S. Uhlmeyer, Washington State Department of Transportation

Abstract: The Washington State Department of Transportation (WSDOT) manages 18,230 lane-miles (29,332 lane-km) of mainline roadway, ranking it 31 out of 50 states in terms of size of state road systems. In the last several years WSDOT has gone through an evaluation and modification of its pavement management practices. The WSDOT evaluation led to two significant conclusions: 1) The historical data show that the flexible pavement network has been very successful in maintaining long-life pavements, resulting in almost no need for reconstruction of flexible pavements. 2) Cost-effectiveness is a very useful performance measure that can be used for making good pavement management decisions. The key performance measure for comparing strategies to maximize service life is Equivalent Uniform Annual Cost normalized by lane-miles into cost per lane-mile per year ($/lane-mile/year or $/LMY). This paper presents the historical perspective on past WSDOT pavement practices and several strategies that were developed to improve the management of pavement assets. WSDOT has been successfully preserving the long life of flexible pavements by applying thin HMA mill and inlays based on the concept that cracking in thicker HMA sections will primarily be top-down. Furthermore, using the framework developed by the evaluation of cost-effectiveness, several strategies have been implemented to improve the management of WSDOT pavement assets. These strategies are: (1) converting 3,000 lane miles (4,827 km) from asphalt to chip-seal resurfacing before the year 2025; (2) planning $0.85 to $1.0 billion rehabilitation and reconstruction for the aging concrete pavement network for the next 10 years where 50 percent of the concrete slated for reconstruction will be converted to flexible pavement using a crack & seat plus asphalt overlay process; and (3) applying strategic maintenance to reduce the annual cost by extending the service life of flexible pavements. These cost-effective strategies are expected to generate an overall annual cost savings of $80 million per year by 2025.

Development and Application of a Roadway/Roadside Life-Cycle Assessment Software for the Illinois Tollway

Paper number 17-06079, http://amonline.trb.org/63532-trb-1.3393340/t009-1.3408027/432-1.3408305/17-06079-1.3400012/17-06079-1.3408313

Authors:
    Rebekah Yang, University of Illinois at Urbana-Champaign
    Wonjae Yoo, University of Illinois at Urbana-Champaign
    Hasan Ozer, University of Illinois at Urbana-Champaign, hozer2@illinois.edu
    Imad L. Al-Qadi, University of Illinois at Urbana-Champaign

Abstract: A roadway/roadside life-cycle assessment (LCA) software is being developed for the Illinois State Toll Highway Authority to assess the environmental sustainability of their network. This paper gives an overview of the software and LCA methodology used, including scope, system boundaries, inventory database, and the software architecture. The rrLCA 1.0 software is the first integrated tool

capable of analyzing multiple elements of the roadway (i.e., drainage, landscape, lighting, pavement, and structures) through its entire life-cycle (i.e., materials and construction, maintenance and rehabilitation, use, and end-of-life). The software is based on pay items, allowing the consideration of a variety of construction activities. Five pavement projects were analyzed, including resurfacing, widening/reconstruction, and new construction contracts. Overall, it was found that the top pay items contributing to the environmental impacts were related to initial pavement construction and rehabilitation overlay activities. In addition, the new construction and reconstruction projects assessed had similar initial construction contributions to the life cycle. The effect of asphalt binder feedstock and calcination was apparent when observing relative differences between predominantly asphalt and Portland cement concrete projects. The life-cycle stage with the greatest environmental impact was the use phase, which contributed 68%–92% of the total global warming potential and 56%–78% of the total primary energy, influenced mainly by traffic volumes and growth. While a comprehensive LCA software such as rrLCA 1.0 can effectively assess the environmental footprint of a road system, it is clear that each project has unique characteristics and parameters that will affect its impact on the environment.

Development of a Performance-Based Model to Integrate Guardrail System Preservation Policies into Asset Management Practices

Paper number 17-06557, http://amonline.trb.org/63532-trb-1.3393340/t001-1.3410589/275-1.3410696/17-06557-1.3400244/17-06557-1.3410697

Authors:
    Shahrouz J. Ghadimi, University of Texas at El Paso, sjafarzadeghadimi@miners.utep.edu
    Sandra N. Gutierrez, University of Texas at El Paso
    Carlos M. Chang, University of Texas at El Paso

Abstract: Asset management (AM) provides a strategic framework for infrastructure systems and focuses on getting the most of their performance with the available resources. To determine future budget needs, highway agencies must have the necessary data and analytical tools to predict the performance of highway assets over time. At present, transportation asset management systems are at different maturity levels. Pavement and bridges are considered the "big ticket" among all highway assets but the preservation of signs, signals, lighting, guardrails, and pavement markings is also crucial to protect road users. In spite of its importance, one of the safety assets with less asset management analytical tools is guardrail systems. Transportation agencies typically replace or repair guardrails that have received major damage due to car crash accidents. To implement a proactive preservation program, in agreement with transportation asset management practices, there are a number of parameters that need to be known. These parameters include inventory information, current guardrail condition, and performance models to forecast changes in the guardrail system condition over time. The objective of this paper is to describe a performance-based model with an analytical method to formulate a proactive preservation program for guardrail systems. The model is developed from inventory data and predicts changes in the guardrail system condition over time. A case study is also presented to estimate the annual agency costs and backlogged costs over a 10-year analysis period. This model can be integrated into an asset management system to facilitate the formulation of preservation programs for guardrail systems at the strategic level.

Economic Feasibility Study for Pavement Monitoring using Synthetic Aperture Radar Satellite Remote Sensing: A Cost-Benefit Analysis

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Authors:
    Mingxin Li, University of Delaware, lmx@udel.edu
    Ardeshir Faghri, University of Delaware
    Abdulkadir Ozden, University of Delaware
    Yixiang Yue, Beijing Jiaotong University

Abstract: Recent developments in satellite remote sensing and availability of high-resolution SAR products have created an opportunity for SAR-based monitoring in pavement and infrastructure management. No previous studies have been carried out in the detailed cost-benefit analysis (CBAs) for analyzing the economic feasibility of pavement monitoring using synthetic aperture radar satellite remote sensing. The aim of this paper is to fill this knowledge gap by proposing a comprehensive methodology to estimate the most important benefit components and expenses associated with the capability of Synthetic Aperture Radar (SAR) satellite data and interferometric synthetic aperture radar (InSAR) for use in advanced infrastructure monitoring and gain a better understanding of the strategies used to identify their effect. A general cost-benefit analysis framework is developed that could serve as a pavement management tool for assessing pavement deformations and deformation velocities with millimetric accuracy. A case study in the State of Delaware is presented to demonstrate how the proposed approaches can be employed to assess the impacts of SAR-based monitoring projects.

Estimating Markov Transition Probabilities for Reinforced Concrete Structures Using Mechanistic-Empirical Models

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Authors:
    Daijiro Mizutani, Swiss Federal Institute of Technology, mizutani@ibi.baug.ethz.ch
    Nam Lethanh, InfraPlus
    Bryan T. Adey, Swiss Federal Institute of Technology
    Kiyoyuki Kaito, Osaka University

Abstract: Current state-of-the-art bridge management systems (BMSs) use Markov models for both the prediction of deterioration and the determination of optimal intervention strategies for reinforced concrete bridges. In using these systems, the results of inspections on bridge elements to determine the condition states of each element are used to estimate the transition probabilities to be used in the Markov models, when they are available over time. In order to use BMSs when they are not available over time, it is necessary to develop a way to estimate transition probabilities to represent the deterioration of bridge elements. One useful way to do this is to use mechanistic-empirical (ME) models. ME models are widely used to model the deterioration of reinforced concrete bridges based on chemical and physical processes, such as chloride induced corrosion and cracking. When a ME model is used, continuous values of deterioration indicators, such as chloride induced corrosion and cracking, can be predicted over time. These values can be then converted into ranges of discrete values and the distribution of discrete values can be estimated at any time step. In this paper, a novel method to estimate the transition probabilities used in Markov models when there is little to no available inspection data is proposed. The proposed method uses two statistical estimation approaches. The first

approach (the analytical approach) is used in situations where it is possible to find an analytical solution so that the transition probabilities can be derived directly from the ME models. The second approach (the Bayesian approach) is used in situations where it is not possible to use the analytical approach. It makes use of Bayesian statistics, which requires the formulation of a likelihood function of the transition probabilities and the use of Markov Chain Monte Carlo (MCMC) methods. The proposed method was demonstrated by estimating the transition probabilities for a reinforced concrete bridge element. In the example, the transition probabilities determined resulted in predicted deterioration from the Markov model that was a good fit with the data generated using the ME model, with high level of confidence. The predicted deterioration was also compared to that estimated when a restricted least squared (RLS) optimization method (a RLS approach) was used to estimate the transition probabilities. It was shown that the sum of the residuals over 30 years when the Bayesian approach was used was approximately 40% smaller than that when the RLS approach was used. In particular, in the example, deterioration was over estimated using the RLS approach.

Implementation of a New Bridge Management System for New York State Department of Transportation

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Authors:
    Shuo Wang, AgileAssets Inc., wangshuocugb2005@gmail.com
    Siamak Saliminejad, AgileAssets Inc.

Abstract: This paper describes the implementation of a new bridge management system (BMS) for New York State Department of Transportation (NYSDOT), aiming to replace the existing management tool. The BMS consists of six main components: bridge inventory and inspection data collection, performance modeling, treatment assignment, project selection models, work plan management, and reporting. A centralized database was created to store bridge inventory and inspection data, which are collected and updated by NYSDOT biennially. Performance models based on second order polynomial functions were used to predict bridge element ratings, from which component condition indices and whole bridge condition ratings were derived. Decision trees were implemented at three levels for elements, components and whole bridges. The existing tool utilized a prioritization method based on a compound priority index to rank candidate projects for funding. The BMS not only implemented the existing prioritization method, but also added an integer programming based optimization method, providing more flexibility and capability to support the decision making process. The selected project candidates form a work plan, which can be shared by the central office and the corresponding regional office through the work plan management component. Various reports such as tables, charts, and maps could be generated based on the analysis results. The major advantages of the new system include: 1. convenient information sharing across various offices due to the centralized database and web-based application; 2. more powerful and flexible analysis abilities to support the decision making process.

Implementation of the Structural Condition Index into the Louisiana Pavement Management System Based on Rolling Wheel Deflectometer Testing

Paper number 17-00404, http://amonline.trb.org/63532-trb-1.3393340/t025-1.3403719/631-1.3404024/17-00404-1.3399698/17-00404-1.3404059

Authors:
Omar Elbagalati, Louisiana State University, oelbag1@lsu.edu
Mostafa A. Elseifi, Louisiana State University
Kevin Gaspard, Louisiana State University
Zhongjie Zhang, Louisiana State University

Abstract: Structural condition data are commonly collected at the project level using Falling Weight Deflectometer (FWD) measurements. However, recent development in continuous deflection devices has offered the potential to characterize pavement structural conditions at the network level. This study introduces a framework for incorporating pavement structural conditions into the Louisiana Pavement Management System (PMS) decision matrix at the network level. The proposed framework aims at filling the gap between network level and project level decisions and eventually, allowing more accurate budget estimation. In this study, Rolling Wheel Deflectometer (RWD) measurements were utilized to evaluate pavement structural conditions in terms of the Structural Condition Index (SCI). Two enhanced decision trees, for collectors and arterials, were developed, such that both functional and structural pavement conditions are considered in the decision-making process. Implementation of the SCI in the decision-making process is demonstrated and is expected to improve the overall performance of the pavement network. Furthermore, the enhanced decision trees are expected to reduce the total maintenance and rehabilitation (M&R) construction costs if applied to relatively high volume roads (e.g., Interstates, Arterials, and Major Collectors).

Long-Term Planning Tool for Pavement Assets

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Authors:
Steven Gillen, Illinois Tollway, sgillen@getipass.com
William Vavrik, Applied Research Associates, Inc.
Thomas P. Wilson, Applied Research Associates, Inc.

Abstract: One of the primary challenges for any transportation agency is to balance and prioritize their needs with respect to maintaining and upgrading their infrastructure assets. For an agency like the Illinois Tollway, the need to align incoming revenue with future maintenance, rehabilitation, capacity enhancements, and reconstruction for their pavements has led to the development of the Pavement Asset Master Plan (PAMP). The PAMP contains basic information about every segment of the Tollway network, its past and current condition, recent traffic levels, and future anticipated maintenance, rehabilitation, and reconstruction activities. The future activities are specific to the mainline and shoulders and are based on predicted performance which was generated using the AASHTO PavementME software, actual experience of pavement performance over time which is based on the Tollway's pavement management system data collected over the past 15 years, and engineering judgement. Since the original version of the PAMP was created five years ago, it has become an important resource for communicating the plan for how Tollway pavements will be maintained and rehabilitated, and it has become an integral part of the long-range planning and budgeting activities at the Tollway. Future enhancements may include the development of a version of the PAMP for all of the

Tollway ramp pavements and a bridge PAMP for the 600-plus structures that are part of the Tollway network.

Managing Network-Level Pavement Condition: An Integer Programming Approach

Paper number 17-06571, http://amonline.trb.org/63532-trb-1.3393340/t025-1.3403719/901-1.3403725/17-06571-1.3403726/17-06571-1.3403727

Authors:
    Md Al Amin, University of Texas at Austin
    Zhanmin Zhang, University of Texas at Austin, z.zhang@mail.utexas.edu

Abstract: Pavement network conditions deteriorate over the years of usage. To keep pavement conditions at an acceptable level, highway agencies plan pavement maintenance and rehabilitation (M&R) programs and perform them accordingly. Highway agencies usually face budget uncertainties for pavement maintenance and rehabilitation activities due to limited resources and changes in government policies. The situation makes it difficult for highway agencies to keep a stable pavement condition at the network level. Therefore, it is important for highway agencies to adopt maintenance and rehabilitation policies that can manage pavement condition at the network level. In this paper, a multi-period multi-objective nonlinear integer programming model is proposed. Two objectives, maximization of average network condition and minimization of fluctuation of network condition from a smooth condition score linear function, are considered in the formulation. The model is formulated for chance constrained M&R budgets. The proposed model provides a maintenance and rehabilitation program for the pavement network that results in stable network conditions. A case study examining a hypothetical network of 25 pavement sections is conducted. The solutions for different chances of budget constraint are presented. Also, the value of the system to the decision maker is discussed. The results show that the proposed model is a practical and flexible way to handle management of pavement maintenance at the network level.

Pavement Management System for Low-Volume Paved Roads

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Authors:
    Marwan Hafez, University of Wyoming, mhafez@uwyo.edu
    Khaled Ksaibati, University of Wyoming
    Rebecca A. Atadero, Colorado State University

Abstract: The most important issue in managing low-volume roads (LVRs) is to define standards and practices applied on roads. In recent years, transportation agencies have dealt with considerable challenges for managing LVRs. These challenges include reductions in maintenance budgets; impact of industrial activities; and ineffective treatments applied on paved roads. The Wyoming Technology Transfer Center (WYT^2/LTAP) conducted online surveys as part of a research project conducted jointly with the Colorado Department of Transportation. The objective of the surveys is to document what the transportation agencies, including state departments of transportation (DOTs), are doing to face these challenges. Four online surveys were sent to the TRB low-volume roads committee, eight DOTs, local governments in Colorado, and the material advisory committee in the Colorado DOT. These surveys have an average of 26 questions dealing with pavement management system (PMS) specifications recommended for low-volume paved roads. Seventy-one transportation agencies responded to the survey. This paper summarizes the responses to the survey showing innovative programs, procedures, and products that are successfully meeting LVRs management needs.

Planning Pavement Maintenance and Rehabilitation Projects in the New Pavement Management System in Texas

Paper number 17-02001, http://amonline.trb.org/63532-trb-1.3393340/t025-1.3403719/569-1.3404062/17-02001-1.3399821/17-02001-1.3404085

Authors:
Feng Hong, Texas Department of Transportation
Eric Perrone, AgileAssets Inc.
Magdy Mikhail, Texas Department of Transportation, Magdy.Mikhail@TxDOT.gov
Ahmed Eltahan, AgileAssets Inc.

Abstract: The Texas Department of Transportation (TxDOT) manages a network of over 197,000 lane miles. Optimum management of the pavement can lead to improved performance at lower costs. TxDOT invested significant effort to develop a new generation pavement management system in the past two years. The new state of the art pavement management system, integrates the engineering experience and research results of over three decades at TxDOT. The capacity of the system includes data archival, database management, mapping, reporting, performance prediction and optimization analysis for decision makers. This paper shows how the new system was used to plan, optimize, analyze, and evaluate pavement maintenance and rehabilitation projects. The advanced analytical functionality of the system is highlighted. As an initial step the new system was used to replace the current four-year plan reporting methodology utilized by TxDOT. The results demonstrate that the new system can serve as an effective tool in support for decision makers, pavement engineers, budget planners, and administrators.

Quantifying Performance Risks and Enabling Process Improvement in Transportation Asset Management

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Authors:
Larry Redd, Redd Engineering, larryreddLLC@gmail.com
William Johnson, Colorado Department of Transportation

Abstract: Various sources of uncertainty, variability, and volatility affect a transportation agency's ability to perform. These sources of uncertainty include project costs, available revenue, project formulation processes, and performance modeling methods. These risks and uncertainties create overall variability in future outcomes and, similar to the manufacturing world, variability is a major cause of unwanted cost and bad performance. In the transportation world, added costs may come from results such as delayed projects which can stem from variable project cost estimates or uncertainty in available revenue. Other added costs may result from poorly bundled projects developed from inconsistent processes and procedures. Finally, if performance modeling capabilities are not accurate or consistent then the inability to reliably forecast performance creates challenges in project planning. In the spring of 2013, as an outcome of their internal assessment regarding asset and risk management capabilities, the Colorado Department of Transportation (CDOT) built a framework for strategically managing assets that includes the ability to manage performance risks. This framework involves the ability to predict performance, in order to look back in time to compare actual performance with the performance predicted years before. By 2014, CDOT was in full swing with this framework, by doing "plan versus actual" comparisons and analyzing the results. By analyzing the variance between forecasted and actual

performance, CDOT is now able to diagnose the root causes of disparities between projected and actual performance. With this knowledge it is possible to reduce variability, improve processes, adjust performance targets, and reach those targets more consistently.

Risk and Resilience Analysis for Highway Assets
Paper number 17-00151, http://amonline.trb.org/63532-trb-1.3393340/t015-1.3406498/499-1.3406570/17-00151-1.3399924/17-00151-1.3406611

Authors:
Elizabeth Kemp Herrera, Colorado Department of Transportation, Elizabeth.Kemp@state.co.us
Aimee Flannery, Applied Engineering Management Corporation
Michael Krimmer, Applied Engineering Management Corporation

Abstract: Transportation agencies own tens of thousands of assets, providing essential mobility and economic services to the communities they serve. Via its Gulf Coast Studies and Climate Change Pilots, FHWA has led efforts exploring the impacts of various physical threats on highway infrastructure and these related services. Moving Ahead for Progress in the 21st Century legislation requires asset managers to implement risk-based asset management, addressing many of the same threats identified in the FHWA GC and Climate studies. In this paper the authors discuss application of one quantitatively based framework (i.e., the RAMCAP Plus™ framework) for analyzing risk posed by such physical threats to highway transportation systems and assets. We recount application of this particular risk analysis framework by the Colorado Department of Transportation following the 2013 floods, supporting federal Emergency Response funding requests. We also examine likely benefits of such analysis for highway transportation project planning and strategic planning.

Two-Stage Data Envelopment Analysis Method for Transportation Infrastructure Maintenance Management
Paper number 17-02484, http://amonline.trb.org/63532-trb-1.3393340/t001-1.3410589/392-1.3410648/17-02484-1.3400066/17-02484-1.3410659

Authors:
Emil Juni, University of Wisconsin-Madison, erjuni@wisc.edu
Teresa M. Adams, University of Wisconsin-Madison

Abstract: Maintenance administrators of transportation infrastructure assets are always facing the challenges of ensuring productive spending and determining the most efficient ways to spend the limited amount of funds and resources available. Efficient resource allocation depends on how efficient the process of maintenance is across all levels of jurisdiction. Especially in states implementing performance-based maintenance management, the knowledge of how efficient a maintenance unit is performing is very important in the state agencies' maintenance investment strategy. A Data Envelopment Analysis (DEA)-based framework allows for efficiency comparison of maintenance units. Implementation of this framework in a decentralized fashion allows for comparison of maintenance units within a specific jurisdictional area, providing results showing the particular time period when maintenance units performed efficiently and inefficiently. However, the non-parametric nature of the DEA method limits the framework to compare efficiencies of units included in a particular comparison model. This study introduces the use of two-stage DEA method to improve the existing DEA framework for efficiency measurement of infrastructure maintenance. This involves regressing the values of the efficiency factors and testing their statistical viability before re-running the values through the DEA model. The inclusion of statistical aspects into DEA framework helps to identify factors with significant

effect on efficiencies of maintenance units. It also increases the validity of efficiency numbers resulted from the efficiency comparison.

Bridge Repair and Rehabilitation

Developing Condition-Based Triggers for Bridge Deck Maintenance and Rehabilitation Treatments
Paper number 17-02652, http://amonline.trb.org/63532-trb-1.3393340/t003-1.3409998/ahd37-1.3410009/17-02652-1.3405679/17-02652-1.3410010

Authors:
    Zhibo Zhang, Purdue University, zhang989@purdue.edu
    Samuel Labi, Purdue University
    Jon Fricker, Purdue University
    Yu Qiao, Purdue University
    Bismark Agbelie, Purdue University
    Kumares Sinha, Purdue University

Abstract: Public agencies have long relied on their experience and subjective judgment to determine when or at what condition to implement bridge deck treatments. This paper attempts to establish appropriate performance thresholds that trigger bridge maintenance and rehabilitation (M&R) activities through analytical approaches. Specifically, latex-modified concrete (LMC) overlay, polymeric overlay (thin deck overlay), routine maintenance and minor repairs, and deck replacement are considered in the analysis as commonly-used bridge deck M&R treatments. The life-cycle cost analysis incorporates both agency costs and user costs. Various weights are assigned to the agency and user costs for the sensitivity analysis. Results indicate that different weighting would have an impact on the optimal trigger that leads to the lowest life-cycle cost. The case study shows that the optimal trigger for LMC overlays should be at wearing surface condition (WS) = 5 if the weight used between agency costs and user costs (AC:UC) > 1.64:1, trigger = 6 if 0.68:1 < AC:UC < 1.64:1, and trigger = 7 if 0 ≤ AC:UC < 0.68:1. For the scenario where both polymeric overlay and LMC overlay are implemented on the same bridge, a polymeric overlay triggered at WS = 6 and an LMC overlay triggered at WS = 5 was found to result in the lowest total EUAC, given AC:UC ≥ 1:1. Condition-based life-cycle deck M&R strategies are proposed based on different trigger results. The original decision tree in the Indiana Bridge Management System was modified to incorporate results from this paper. It is expected that the data-driven analysis and results of this study could help agencies enhance their decisions with regard to the timing of some particular bridge deck treatments.

Retrofitting Damaged Bridge Elements Using Thin Ultra High Performance Shell Elements
Paper number 17-02047, http://amonline.trb.org/63532-trb-1.3393340/t003-1.3409998/534-1.3410175/17-02047-1.3405788/17-02047-1.3410180

Authors:
    Alireza Valikhani, Florida International University, avali023@fiu.edu
    Azadeh Jaberi Jahromi, Florida International University
    Atorod Azizinamini, Florida International University

Abstract: Bridge structures could be exposed to severe environmental conditions, resulting in reduced durability and service life and demanding replacement or repair. This paper provides an alternative for retrofitting bridge elements using a thin layer of Ultra-High Performance Concrete (UHPC) in a configuration that covers the damaged area and attaches to the elements. This thin shell can be designed in a variety of shapes, installed easily, and can increase the strength of bridge elements. In addition, it minimizes future corrosion, while reducing cost and time. In this experimental study, three beam specimens were used to proof test the proposed method. One specimen was used as a reference point and did not incorporate any damages. The second specimen included a damage, which simulated section loss. The third test specimen incorporated the same level of damage as the second test specimen and was retrofitted using the proposed retrofit method. A comparison of the results showed that the retrofitted beam effectively gained 18% of the capacity of the damaged beam. The material presented in this paper is a proof of concept. Additional tests are being conducted to develop a complete set of information for field implementation of the suggested retrofitting methodology.

Using Life-Cycle Cost Analysis for Maintaining Concrete Bridge Decks in Pennsylvania

Paper number 17-05504, http://amonline.trb.org/63532-trb-1.3393340/t003-1.3409998/241-1.3410333/17-05504-1.3400294/17-05504-1.3410335

Authors:

Shervin Jahangirnejad, Quality Engineering Solution, Inc., sjahangirnejad@QESpavements.com
Dennis Morian, Quality Engineering Solution, Inc.
Aleksandra Radlinska, Pennsylvania State University
Farshad Rajabipour, Pennsylvania State University

Abstract: Life-cycle cost analysis (LCCA) activities are presented for evaluating alternative bridge deck preservation strategies over the useful life of concrete bridge decks in Pennsylvania. Performance information was taken from data collected from the field inspection of deck cracking in forty concrete bridge decks, and performance data from over 200 additional decks contained in the Pennsylvania Department of Transportation (PennDOT) bridge inspection database. A performance model based on 22,000 bridge data provided information about the change in deck condition over time. Additional information including which preservation treatments are used by PennDOT and the performance life of these treatments was based on expert opinion from the PennDOT staff. Life-cycle cost analyses were performed using the FHWA RealCost program. of LCCA to bridge decks, and providing cost comparisons of bridge deck preservation strategies including the use of different treatments, treatment sequences, and application timing. Typical deck preservation treatments include latex-modified concrete overlays, epoxy overlays, and waterproofing membrane & bituminous overlay. Results generally indicate that fewer, longer lasting preservation strategies provide the best cost effectiveness over the analysis period. In order to achieve enhanced performance, additional analyses were carried out based on both performance life and service life predictions. The service life predictions are based on the prediction of life based on the materials components using the LIFE-365 model. This service life prediction is a micro level assessment, and is based on the prediction of critical rebar corrosion in the bridge decks.

Condition Assessment

Characterization of Steel Bridge Superstructure Deterioration through Data Mining Techniques

Paper number 17-02296, http://amonline.trb.org/63532-trb-1.3393340/t003-1.3409998/375-1.3410235/17-02296-1.3409374/17-02296-1.3410240

Authors:
Cristian Contreras-Nieto, Oklahoma State University, contrec@okstate.edu
Yongwei Shan, Oklahoma State University
Phil Lewis, Oklahoma State University

Abstract: As a significant number of steel bridges are approaching the end of their service life, understanding deterioration characteristics will help bridge stakeholders better prioritize bridge maintenance, repair, and rehabilitation. This paper applies data mining techniques including logistic regression, decision trees, neural networks, gradient boosting, and support vector machine to the 2013 National Bridge Inventory to estimate the probability of steel bridge superstructures reaching deficiency. Deterioration factors considered included age, average daily traffic, design load, maximum span length, and structure length. The impacts of these factors affecting steel bridge superstructure deterioration were identified. Outcomes of the analysis afford bridge stakeholders the opportunity to better understand factors that relate to steel bridge deterioration as well as provide a means to assess other risks associated with bridge maintenance, repair, and rehabilitation.

Crack-Growth Detection for Asphalt Pavement Using Infrared Imaging

Paper number 17-02694, http://amonline.trb.org/63532-trb-1.3393340/t005-1.3409009/207-1.3409783/17-02694-1.3401499/17-02694-1.3409799

Authors:
Yuchuan Du, Tongji University
Xiaoming Xhang, Tongji University, lcl_tongji@126.com
Feng Li, Research Institute of Highway
Lijun Sun, Tongji University

Abstract: The degree of crack growth in asphalt pavement is an important decision-making factor in road-maintenance management. Automatic crack detection is based mainly on digital images, which makes it difficult to detect the degree of crack growth effectively. We used infrared thermography and proposed a detection method for the degree of crack growth based on infrared imaging. Infrared images include gray-level information on cracks and temperature information; the latter provides one additional dimension of information over ordinary images. We used temperature information to detect the degree of crack growth. Atmospheric temperature was found to be the main factor that affects the temperature difference between the crack and the road surface. This temperature difference varied significantly for different extents of crack growth and therefore, we can use this difference to detect the degree of crack growth. Two classification functions that divide the degree of crack growth into three grades were obtained by classifying data using a support vector machine. We proposed suitable environmental conditions for using the detection model. The experimental results show that the average model error is 15.4%, which indicates a good application prospect and an improvement in economic benefit for pavement maintenance.

An Evaluation Framework for Automated Pavement Distress Identification and Quantification Applications

Paper number 17-03557, http://amonline.trb.org/63532-trb-1.3393340/t005-1.3409009/519-1.3409288/17-03557-1.3399899/17-03557-1.3409291

Authors:
    Nima Kargah-Ostadi, Fugro Roadware, Inc., nkargah-ostadi@fugro.com
    Abdenour Nazef, Florida Department of Transportation
    Jerome Daleiden, Fugro Roadware, Inc.
    Yuxiao Zhou, Fugro Roadware, Inc.

Abstract: Tracking pavement deterioration types and extent is critical to maintain road networks in a serviceable condition. The prevailing methods for obtaining pavement condition data include manual and semi-automated surveys, which are time-consuming and involve significant human intervention. In response, extensive research has been performed in automating the process for more efficient, objective and repeatable distress evaluations. This paper highlights the preliminary results from an effort sponsored by the Florida Department of Transportation to develop and implement an automated software for identification and quantification of pavement surface cracking distresses. A technical framework was developed for systematic evaluation of available automated technologies in contrast to manual methods. Pertinent performance measures were identified to evaluate the accuracy, precision, repeatability, reproducibility, and efficiency of various methods. This framework was implemented to determine the gaps in effectiveness of automated applications, design corresponding solutions, and gauge reliability expectations accordingly. The evaluation follows two main steps: 1) comparison of the cumulative quantities of various distress types found in the manual versus automated surveys, and 2) verification of the automatically detected distresses against reference crack maps generated through a semi-automated process of manually rating the collected images. While the overall comparison of distress quantities provides an indication of strengths and weaknesses of the evaluated algorithm, the distress by distress verification of software performance is used to identify design solutions to address the indicated weaknesses. The guidelines in this systematic framework can be modified with context-sensitive considerations to be applicable to other highway agencies seeking a transition towards automated applications.

A Framework for Effective Utilization of NDE and SHM for Safety and Preservation Applications

Paper number 17-02210, http://amonline.trb.org/63532-trb-1.3393340/t003-1.3409998/ahd37-1.3410009/17-02210-1.3405680/17-02210-1.3410011

Author:
    John C. Duke, Jr., Virginia Tech, jcduke@vt.edu

Abstract: Assuring and preserving the safety and structural integrity of bridge structures involves optimally balancing a number of factors including: Quality of materials used at construction, quality of the construction, geotechnical factors associated with the bridge structure location, environmental factors, changing user demographics, aging inventory, known and perceived life-cycle cost benefits of preservation and repair options, lack of experience with rapidly evolving NDE/SHM instrumentation, competing system-wide needs, organizational impediments, political constraints, personnel and financial resources. Rumors of glowing successful applications and dismal failures cause interest as well as reluctance to consider using nondestructive evaluation (NDE) and structural health monitoring (SHM)

technologies. Moreover proponents offer one-dimensional arguments for using NDE or SHM which ignore many of the factors which must ultimately be balanced by bridge custodians, typically State DOTs. A framework is described here which, while not addressing all of the factors above, provides for options based on strategies which bridge custodians have evolved for balancing their specific combination of complicating factors. This framework uses as a starting point the significant bridge elements identified in the Manual for Bridge Element Inspection, (MBEI) (1) and suggests when and how NDE, SHM, or some combination might be used if it aligns with the established strategies. It is expected as greater experience with such approaches is gained, and increased knowledge regarding the life-cycle cost benefits of interventions for optimizing bridge performance developed, more wide-spread use of NDE and SHM will occur; ideally this will drive down the costs and increase the reliability of such technologies.

Innovative Approaches to Pavement Condition Data Collection

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Authors:

    Eric Paul Dennis, Center for Automotive Research, EPDennis@cargroup.org

    Adela Spulber, Center for Automotive Research

    Richard Wallace, Center for Automotive Research

Abstract: This paper highlights a series of novel and developing methods of pavement condition assessment using advancing technologies. The data collected by these methods can be used to improve pavement performance management, infrastructure investment decisions, and broad transportation asset management and planning efforts. This information is intended for transportation and planning agencies who wish to explore novel technology-enabled methods to improve pavement performance management within a comprehensive performance-based transportation asset management system. Five categories of pavement data collection are discussed herein: smartphone accelerometry indices, crowdsourced pavement condition data, automated vehicle systems data, in situ structural health monitoring, automated distress classification

Integration of TSD and GPR for Network-Level Pavement Structure Evaluation and Geodatabase Development

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Authors:

    Kenneth Maser, Infrasense, Inc., kmaser@infrasense.com

    Pete Schmalzer, Nichols Consulting Engineer

    Bill Shaw, Idaho Transportation Department

    Adam Carmichael, Infrasense, Inc.

Abstract: The project has focused on the East Idaho Loop Corridor (EILC), representing 515 miles of primary roadways covering a wide range of geographic conditions. The Idaho Transportation Department (ITD) has pursued this effort to support future project planning and design efforts and advance the management of their assets into a more efficient, Best-First, set of priorities. The EILC was surveyed with a Traffic Speed Deflectometer (TSD) and with Ground Penetrating Radar (GPR). After preliminary review of the TSD data, segments were selected for Falling Weight Deflectometer (FWD) testing to confirm patterns observed in the TSD data and to adapt FWD analysis methods to the TSD data. Ninety-nine borings were taken to confirm the pavement layer structure and verify thickness

calculations. The TSD data was analyzed at a 10- meter interval with the GPR layer thickness data to determine subgrade modulus, pavement modulus, and structural number. These values were then used to estimate overlay requirements, and, given traffic projections, to calculate the remaining life as a continuous function of roadway position. The data was incorporated into a spatial geodatabase that provides ITD with a convenient means to visualize and evaluate the overall condition of the network down to the detail of its individual segments. The segments have been subdivided into "homogenous" subsections based on remaining life, and these sub-segments have been used for identifying and programming rehabilitation projects. The level of condition detail available at the sub-segment level allows for pavement design and for scoping restoration projects.

Inventory-Based Rating System: Stable and Implementable Method of Condition Assessment for Unpaved Roads

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Authors:
    Timothy Colling, Michigan Technological University, tkcollin@mtu.edu
    John Kiefer, Michigan Technological University
    Peter Torola, Michigan Technological University

Abstract: The current rating systems for unpaved roads lack stability and reliability and, therefore, provide little benefit as a project- or network-level metric. Since many of these systems are derived from paved road assessment systems, they focus heavily on surface distresses rather than road width, drainage, and other features. Because unpaved roads can change rapidly, measuring surface distresses is an unreliable rating factor. The Inventory-Based Rating (IBR) system assesses unpaved roads on Surface Width, Drainage Adequacy and Structural Adequacy. These features impact road users and have significant costs associated with creation and maintenance. The system defines a baseline condition for each inventory feature with its tiered good-fair-poor rating. Five counties, selected based on their road network classification, participated in a pilot IBR data collection. User feedback was also collected from participants. The study showed very high repeatability and reliability of the IBR system. It also provided productivity benchmarking, which can forecast the time commitment for data collection. User feedback resulted in modifications to the system.

Pavement Crack Detection Using Directional Curvature

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Authors:
    Yalan Ding, Wuhan University
    Yuchun Huang, Wuhan University, hycwhu@whu.edu.cn
    Liu He, Wuhan University

Abstract: Pavement crack is one of the important indicators of pavement conditions that are necessary for the correct and timely maintenance operations in transportation agencies. Video log pavement images are collected to identify the cracks automatically or semi-automatically. However, due to the device noise, improper lighting, pavement textural mixture, surface debris, etc, imaging conditions of pavement crack images vary a lot. Automatic detection of pavement crack from those images remains a challenge. This paper is motivated to develop a new perspective of characterizing pavement crack. Unlike the traditional edge based crack detection, the proposed algorithm locates crack pixels in the

pavement image using the directional curvature along the 3-D valley of pavement crack. Continuous cracking is composed of the connection of neighboring profile of 3-D crack valley along the direction of cracking. Curvature at different point of the profile varies with its different depth from the pavement surface. A normalized pavement surface is obtained by Gaussian smoothing of different imaging conditions. Multi-scale directional curvature of the crack valley profile is then calculated to best accommodate with its actual scale. With the strategy of edge drawing, false detection of short crack-like valley structure is controlled by the minimal level of significance of the interconnection of the optimal directional crack curvature. Centerline of the pavement crack valley is finally delineated using the morphological and thinning operations. The proposed algorithm is tested on a diverse set of actual pavement images taken on interstate highway G-4 near Beijing, China under varying lighting conditions and shadows. A buffered hit percentage is used to quantitatively evaluate the accuracy of the proposed algorithm. Experimental results show the proposed algorithm detects well the crack pixels with the hit percentage of 100%. It is promising for the automatic classification and severity evaluation of pavement crack in the intensity and range images.

Performance Measures for the Assessment of the Condition of Bridges: A Critical Review
Paper number 17-05179, http://amonline.trb.org/63532-trb-1.3393340/t003-1.3409998/241-1.3410333/17-05179-1.3400295/17-05179-1.3410337

Authors:
    Ehsan Fereshtehnejad, Ohio State University, fereshtehnejad.1@osu.edu
    Jieun Hur, Ohio State University
    Abdollah Shafieezadeh, Ohio State University

Abstract: Bridges are among the most essential and important transportation assets. Since they comprise various ages, configurations, and structural features, and are exposed to different environmental conditions and service loads, evaluating their performance and managing their safety and serviceability is challenging. A number of state DOTs and federal agencies have developed and implemented several bridge performance measures in the past several decades. This study explores existing bridge performance measures through an extensive literature review, presents their concepts and applications, and discusses their unique features. The measures include metrics proposed/implemented by state DOTs, FHWA, NCHRP, and other researchers in the U.S. and around the world. Results of this study will assist stakeholders in choosing appropriate metrics for various performance assessment and management purposes. In addition, identified gaps in existing metrics can guide in the development of efficient performance measures for bridge systems.

Culvert Repair

Culvert and Storm Drain Inspection Manual
Paper number 17-05544, http://amonline.trb.org/63532-trb-1.3393340/t003-1.3409998/520-1.3410183/17-05544-1.3410184/17-05544-1.3410185

Authors:
    Matthew C. Richie, Simpson Gumpertz & Heger Inc., mcrichie@sgh.com
    Jesse L. Beaver, Simpson Gumpertz & Heger Inc.

Abstract: The authors of this paper have recently completed the National Cooperative Highway Research Program (NCHRP) Project 14-26, which produced the Culvert and Storm Drain System Inspection

Manual. This new manual updates and replaces the 1986 FHWA Culvert Inspection Manual, which has for the past three decades served as the primary resource for evaluating distress in highway and railway culverts. This paper introduces the new manual and highlights important aspects of the inspection process. The new manual has been made available to AASHTO for consideration for adoption, with expected publication in 2017.

Current State of Small Culvert Inspection & Inventory in the United States
Paper number 17-01560, http://amonline.trb.org/63532-trb-1.3393340/t003-1.3409998/520-1.3410183/17-01560-1.3399897/17-01560-1.3410191
Authors:

Natalie Villwock-Witte, Montana State University, n.villwockwitte@montana.edu
David Hadwiger, New Mexico Department of Transportation
Karalyn Clouser, Montana State University
Laura Fay, Montana State University

Abstract: Like many state departments of transportation (DOT) grappling with the need to address aging infrastructure, the New Mexico DOT initiated a study on the state of the practice for small culvert inspection and inventory. The researchers reviewed literature and deployed a survey that was sent to all fifty state DOTs, from which, all but three state DOTs provided a response. Findings from this research effort include: 1) nineteen states are currently inspecting and inventorying culverts within their bridge inventory that extend beyond the definitions specified in the Code of Federal Regulation 23 650.305, 2) approaches to small culvert inspection and inventory are changing over time, and 3) the magnitude of small culverts is staggering, in some states numbering in the hundreds of thousands. How a state defines a small culvert can impact the number of culverts identified. Some recommendations based on the findings include: 1) use the approach implemented by the Vermont DOT to assist local entities with small culvert asset management, essentially creating a repository for culverts statewide, as a best practice, and 2) employ a tiered approach to small culvert inspection to balance staffing resources with the number of small culverts. Two primary needs were identified as a result of the research effort: 1) implementation of a culvert failure reporting system (similar to the fatality analysis reporting system) to improve documentation of culvert failures (including small culverts) and enhance understanding of their causes. 2) development of a nation-wide training specific to small culvert inspection.

Emergency Maintenance Operations

Enhancing Resilience of Bridges to Extreme Events by Rapid Damage Assessment and Response Strategies
Paper number 17-05021, http://amonline.trb.org/63532-trb-1.3393340/t015-1.3406498/499-1.3406570/17-05021-1.3399919/17-05021-1.3406587
Author:

Alice Alipour, Iowa State University, alipour@iastate.edu

Abstract: The U.S. highway transportation network consists of more than 650,000 bridges that are essential to maintaining the performance of the network. The existing bridges are, however, vulnerable to a variety of natural and manmade hazards and may act as "bottle necks" in case of any failures. The most common extreme events include natural hazards such as ground excitation during earthquakes,

high wind and storm surge in hurricanes, and scouring and debris impact during floods. Despite several advances in the available technologies for the design of new bridges and the retrofit of the existing ones, there are still incidents that the bridges fail partially or completely after an extreme event. In such cases, it is important for the federal, state, and local authorities to identify the damaged bridges, quantify the extent of damage, plan for rapid recovery, and also provide alternative routes for the emergency response and evacuation activities. For this purpose, NCHRP Synthesis Topic 46-11 gathered the relevant information on the technologies that are available for rapid post-extreme event damage assessment of the highway bridges, the availability of data from these techniques to transportation agencies and bridge owners, decision making tools or processes that would use the data, and the emergency planning protocols in place to address the failures in bridges. This paper provides a summary of the findings of this project.

Fleet Management

Fleet Replacement Methods Evaluation and Refinement
Paper number 17-04924, http://amonline.trb.org/63532-trb-1.3393340/t021-1.3405667/ahd60-1.3405669/17-04924-1.3400370/17-04924-1.3405670

Authors:
Yingjing Zhu, University of California Riverside, yzhu018@ucr.edu
George Scora, University of California Riverside
Michael Todd, University of California Riverside

Abstract: This paper investigates the vehicle equipment replacement decision making methodologies available to the California Department of Transportation (Caltrans) and other similar vehicle fleet operations. The goal is to optimize the replacement timing of aging vehicle equipment to minimize total costs and maintain certain fleet characteristics; such as, fleet reliability and preparedness. In this paper, an overview and discussion of key factors for vehicle equipment replacement decision making and various Fleet Replacement Methods (FRM) utilized by Caltrans and other states' Department of Transportation (DOT) are presented. Aspects of more than 5 different FRMs in 3 different FRM categories are compared and summarized, and results are provided in the paper. An in depth analysis is presented focusing on the most applicable alternative to Caltrans' current FRM, i.e. a popular analytical technique called Life Cycle Cost Analysis (LCCA). The major tasks in this work include building a LCCA Model, utilizing Caltrans' fleet data, processing and visualizing fleet data, accurately modeling cost trends to predict future costs, evaluating the feasibility and constrains, and applying an enhanced method to optimize the model. The primary objective of this research is to develop a tailored FRM and facilitate the decision making process for replacing equipment within Caltrans' vehicle fleet.

Funding and Budgeting

Development of a Cost Index for In-House Roadway Maintenance Work for the North Carolina Department of Transportation

Paper number 17-01670, http://amonline.trb.org/63532-trb-1.3393340/t001-1.3410589/392-1.3410648/17-01670-1.3400067/17-01670-1.3410661

Authors:
John Hildreth, University of North Carolina Charlotte, John.Hildreth@uncc.edu
Scott Capps, North Carolina Department of Transportation

Abstract: Maintenance activities represent a significant portion of roadway lifecycle costs and a cost index representing changes in maintenance costs over time is useful to State Highway Agencies (SHA) for developing multi-year work plans and budgets. The Highway Maintenance and Operations Cost Index previously maintained by FHWA was discontinued in 1990. Since that time, SHAs have met the need for a maintenance cost index with the use of available cost indices that are not specific to roadway maintenance. Cost indices were developed for the North Carolina Department of Transportation to represent in-house maintenance work in the Roadside, Maintenance, Traffic, and Bridge categories of the Standing Maintenance budget and combined into a composite index for Roadway Maintenance. This paper presents the rationale for selecting the fixed-base Laspeyres index form and the methods for selecting the basket of tasks and calculating the indices from work order task records. The resulting index values are presented and the observed annual cost increases are compared to the annual increases reflected by the previous Highway Maintenance and Operations Cost Index.

Economic Analysis of InSAR Technology Application in Transportation

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Author:
Audrey K. Moruza, Virginia Transportation Research Council, Audrey.Moruza@VDOT.Virginia.gov

Abstract: The economic analysis described in this paper was performed to assist the Virginia Department of Transportation (VDOT) in evaluating the use of satellite-based Interferometric Synthetic Aperture Radar (InSAR) technology for remote detection and monitoring of surface deformations that impact roadways and other assets maintained by VDOT. The analysis guides a decision for a short term trial rather than a long term practice on the principle that, during a trial, new capabilities of an established technology can appear opportunistically and concurrently with expected benefits as field implementation progresses. Alternatively, if they do not appear, VDOT has not committed to the technology. The question posed in this analysis is how the costs for processed InSAR maps of surface deformation compare to VDOT's potential cost savings in two maintenance activities which could in theory be mitigated by early intervention resulting from advance detection of ground settlement. The findings suggest that VDOT's costs for these event categories relative to the cost of medium resolution InSAR data are sufficient to justify consideration of a technology "lease" period, during which additional benefits from wide area monitoring could be explored. Additionally, under relatively conservative assumptions of detection rates (reflecting technology effectiveness) and savings rates (reflecting agency response), the analysis suggests that potential savings are sufficient over a 5-

year analysis period with medium resolution InSAR data to provide funds for high-resolution follow-up frames featuring "hot spots" or locations of special significance.

The Economics of Integrating Innovative Monitoring Technologies into Bridge Management Policy

Paper number 17-04030, http://amonline.trb.org/63532-trb-1.3393340/t003-1.3409998/241-1.3410333/17-04030-1.3400297/17-04030-1.3410341

Authors:
    Paul B. Westcott, Pomona College, pbw02014@pomona.edu
    Faezeh Azhari, University of Toronto

Abstract: Presumed structurally deficient bridges may deserve a second chance. In this study, three management policies incorporating innovative monitoring schemes were investigated using an exploratory economic model. The model focused on decisions regarding bridges that were diagnosed as structurally deficient through visual inspections (VI). Three policies were considered: Policy I was to rebuild the bridge, while Policies II and III used various testing and monitoring schemes to determine if the bridge is actually structurally deficient and in need of replacement. Load rating tests (LRT) and structural health monitoring (SHM) were incorporated into Policy II. Policy III supplemented LRT and SHM with an additional low-cost testing method referred to as the digital signature (DS), which measures the deflection profile of the bridge. The results of this exploratory economic model show that for a fleet of 100 bridges, there is a major economic benefit if Policy II is used over Policy I. The results showed further savings using Policy III if DS testing is at least 50% accurate. DS testing is relatively inexpensive and can therefore reduce the overall costs by adding another layer of testing between VI and monitoring. Policy III allows bridge managers to have a truly hybrid approach to bridge asset management. Overall, the economic benefits provide an impetus for monitoring bridge networks to confirm and supplement inspection results.

Probabilistic Characterization of Life Cycle Agency and User Costs: A Case Study of Minnesota

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Authors:
    Mehdi Akbarian, Massachusetts Institute of Technology, akbarian@mit.edu
    Omar Swei, Massachusetts Institute of Technology
    Randolph Kirchain, Massachusetts Institute of Technology
    Jeremy Gregory, Massachusetts Institute of Technology

Abstract: Life cycle cost analysis (LCCA) is a commonly used approach by pavement engineers to compare the economic efficiency of alternative pavement design and maintenance strategies. Over the last two decades, the pavement community has augmented the LCCA framework used in practice by explicitly accounting for uncertainty in the decision-making process and incorporating life-cycle costs not only to the agency but also to the users of a facility. This study represents another step towards improving the LCCA process by (a) focusing on methods to characterize the cost of relevant pay items for an LCCA as well as (b) integrating costs accrued to users of a facility due to pavement vehicle interaction (PVI) and work zone delays. The authors implement the developed model in a case study to quantify the potential implication of both of these components on the outcomes of an LCCA. Results from the construction cost analysis suggest that the proposed approaches in this paper lead to high fidelity estimates that outperform current practice. Furthermore, results from the case study indicate

that PVI can be a dominant contributor to total life-cycle costs and, therefore, should be incorporated in future LCCAs.

Pavement Repair and Rehabilitation

Characterization of a Material Sealant for Cracks in Flexible Pavements

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Authors:
    Peréz Rea Maria de la Luz, University Autonomous of Queretaro
    Hernández Padrón Genoveva, National Autonomous University of Mexico
    Reyes Uzárraga Gustavo, University Autonomous of Queretaro, gustavo_reyes19@hotmail.com

Abstract: The flexible pavement is the most used for the coating of roads due to its numerous advantages, however, the main disadvantage is the appearance of cracks on surface, which if they are not treated in a timely manner can cause damage to the infrastructure more you record and reduce the efficiency of the same. Therefore, the cracks should be treated effectively. The method of sealing of cracks it is highly used in flexible pavements, but has some difficulties, which is why sealing materials must present characteristics of adhesion, hardness, and resistance to water filtration. The present paper shows the development of a sealant based resin funcionalizada epoxy, which was placed on a stretch of test and subjected to weathering, allowing to know in this way his behavior. The results obtained show that in them conditions of weathering to which was submitted the sealer, this has a behavior acceptable, decreasing in a 20% the intrusion of water to layers underlying, besides a null loss of groups functional present.

Chicago's Lake Shore Drive: A Case Study for Rapid Response to Blowups and Concrete Joint Investigation

Paper number 17-06425, http://amonline.trb.org/63532-trb-1.3393340/t004-1.3409814/736-1.3409837/17-06425-1.3399519/17-06425-1.3409838

Authors:
    Joe Pitlik, S.T.A.T.E. Testing LLC, jpitlik@statetestingllc.com
    Sarah Kilroy, S.T.A.T.E. Testing LLC
    Cynthia Williams, Chicago Department of Transportation

Abstract: Lake Shore Drive (LSD) is a major thoroughfare on the western bank of Lake Michigan that connects the City of Chicago to the northern and southern suburbs. The roadway in composed of jointed plain concrete pavement with epoxy coated dowel bar reinforcement in the transverse joints. With its impressive views and large average daily traffic (ADT), this particular stretch of pavement is a very important and visible component of the City's traffic system. Extreme weather exposure combined with an aging pavement system led to multiple pavement failures, specifically blowups that snarled traffic and posed a significant logistical challenge to the Chicago Department of Transportation (CDOT). S.T.A.T.E. Testing, LLC, as part of CDOT's Independent Testing team, was tasked with working with the city's engineering and maintanence group to formulate and oversee a repair procedure that would eliminate further distresses, and restore long-term ride quality and structural stability while meeting the City's significant logistical constraints for traffic closures. In addition, it was determined that, within the

limits of each night's closures, S.T.A.T.E. Testing, LLC should take advantage of the closures by performing as much MIT-Scan 2 testing as possible to evaluate the condition of the remaining joints. This data will be useful in helping determine future exposure to potential blowouts and in developing revised specifications that can increase the overall quality of concrete pavement joints in future construction. Conclusions about the effectiveness of the chosen repair methods and existing joint construction specifications are made.

A General Iterative Approach for the System-Level Joint Optimization of Pavement Maintenance, Rehabilitation, and Reconstruction Planning

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Authors:
    Le Zhang, Hong Kong Polytechnic University, le.zhang@connect.polyu.hk
    Weihua Gu, Hong Kong Polytechnic University
    Yaohua Hu, Shenzhen University

Abstract: Pavements deteriorate fast, partly due to the rapidly growing traffic volumes. To defer the deterioration and extend pavements' service life, preventive maintenance, rehabilitation and reconstruction (MR&R) activities have been applied in the practice. Each of the three treatments has distinct effect on a pavement's current condition and further roughness development. Unfortunately, the present models are incapable of jointly optimizing the planning and scheduling of all the three treatments for a large system of pavement segments. This is mainly due to the greater complexity incurred by the more realistic but complicated segment-level models that have been used in recent years. This paper proposes an iterative approach to developing the optimal MR&R plan that minimizes the total user and agency costs for heterogeneous pavement systems under agency budget constraints. The proposed approach decomposes the system-level problem into segment-level subproblems, whose solutions are much easier to develop. Our approach is general in that it does not depend upon specific models at the segment level. It is thus able to address more engineering realism (e.g. history-dependent deterioration and realistic maintenance effectiveness) than any previous work. Numerical case studies that incorporate such realism are examined to verify our approach. Insights derived from these case studies are also discussed.

Innovative Maintenance, Repair, and Reconstruction Techniques for Asphalt Roadways: A Survey of State Departments of Transportation

Paper number 17-04946, http://amonline.trb.org/63532-trb-1.3393340/t004-1.3409814/736-1.3409837/17-04946-1.3403790/17-04946-1.3409840

Authors:
    Baris Salman, Syracuse University, bsalman@syr.edu
    Ossama (Sam) Salem, Syracuse University
    Danielle T. Garguilo, Syracuse University
    Song He, Syracuse University

Abstract: Highway networks in the United States have been suffering from poor operational and structural condition states for the past decades. The consequent congestion problems have resulted in large amounts of delays, fuel consumption, greenhouse gas emissions, and safety issues. With limited funding available, management of congested highways has become more challenging due to higher rates of deterioration and higher user costs. Therefore, transportation agencies and local agencies are

placing more emphasis on innovative maintenance, repair, and rehabilitation (MRR) techniques that have the potential to reduce the economic, social, and environmental impacts associated with traditional techniques. As a part of a research project, the authors are investigating various innovative MRR techniques that can be employed to improve the conditions of asphalt roadways. The objective of the project is to develop a high-level decision support tool that will assist agencies in determining the most suitable MRR technique under various scenarios. In this paper, the initial findings of this project are presented. A review of literature on current innovative MRR methods is provided along with the results of a survey of state departments of transportation (DOTs). Specifically, uses of warm mix asphalt, full depth reclamation, recycled asphalt pavements (RAP), cold in-place recycling, and intelligent compaction are discussed. The basic features and characteristics of each technique, along with the survey results demonstrating the current usage rates and challenges associated with these techniques for state DOTs, are provided.

A Novel Control Pothole Repair System Using Radiant Heat for Long-Lasting Patch Repairs
Paper number 17-01917, http://amonline.trb.org/63532-trb-1.3393340/t021-1.3405667/450-1.3405815/17-01917-1.3404111/17-01917-1.3405820
Authors:

Juliana Byzyka, Brunel University, juliana.byzyka@brunel.ac.uk
Denis Albert Chamberlain, Brunel University
Mujib Rahman, Brunel University

Abstract: Typical hot pothole repairs include temporary and permanent solutions that are highly affected by detracting factors such as poor interface bonding between host pavement and hot fill material. This based in their different mass temperatures. To address the issue a novel prototype Control Pothole Repair System (CPRS) that preheats the excavated pothole prior to its repair is suggested. The CPRS includes a number of innovative features including multiple motion controlled radiant heaters and positioning information. Current practices have used heating for removal of defected material and ensuring that surface temperature of fill pothole is sufficiently high. The authors believe that only doing the above is not in itself a sufficient measure for ensuring bonding with introduced fill. This holds that it is necessary to preheat the excavated pothole prior to its repair. The reported study relates the initial development of CPRS, its heating capabilities and pothole excavation preheating by it. All the experiments are laboratory based executed to a single size pothole this constituting initial stages of a wider research being developed by the authors towards longer lasting pothole repairs. Outcomes demonstrate temperature distribution below and on the heater plate, pothole preheating with consideration of cooling influences and significant temperature differentials between pothole excavation base and boundaries. The latter suggests weakness in common hot pothole repair practice. The laboratory outcomes are used to effectively calibrate a three dimensional finite element thermal model of the pothole heating process, this intended to be part of a future control algorithm for the heater.

Performance-Related Specifications for Asphalt Emulsions Used in Microsurfacing Treatments

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Authors:
Mohammad Ilias, Fugro Roadware, Inc.
Javon Adams, North Carolina State University
Cassie Castorena, North Carolina State University
Y. Richard Kim, North Carolina State University, kim@ncsu.edu

Abstract: This paper details the development of a framework for emulsion performance grade (EPG) specifications for microsurfacings. Microsurfacings are preservation surface treatments designed to improve the condition of the pavement surface while mitigating deterioration of the overall pavement structure. Asphalt emulsions used in microsurfacings often are selected based on factors that are not necessarily related to performance. Rutting and thermal cracking have been identified as the most critical microsurfacing distresses related to binder performance. To assess fresh emulsion properties, storage stability and mixability have been determined to be the most critical constructability concerns. For this study, binder and mixture test methods were identified to reflect the failure mechanisms for each critical distress type. Emulsion residue test methods that were identified to capture microsurfacing performance are the multiple stress creep and recovery test for rutting and the dynamic shear rheometer frequency sweep test for thermal cracking. The identified critical fresh emulsion properties that relate to constructability include storage stability and viscosity measured at a low shear rate. The proposed EPG specifications for fresh emulsion properties related to constructability were developed using statistical analysis of the binder test results. The EPG specifications for residual binder were developed by defining the temperature-independent relationships between the emulsion residue properties and the mixture performance that correspond to each critical distress. Preliminary specification limits were then established based on the values of the binder properties that correspond to the critical mixture performance thresholds.

Performance Modeling

Climate Change Impact on Management of Deteriorating Bridges: A Case Study of U.S. Midwest Region

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Authors:
Dena Khatami, Iowa State University
Behrouz Shafei, Iowa State University, shafei@iastate.edu

Abstract: A large number of reinforced concrete (RC) bridges located in the U.S. are at least 50 years old and during their service life are exposed to environmental stressors. As a consequence, the bridges have degraded due to ingress of aggressive ions, such as chlorides. Although the deterioration of bridges has been studied in the field and numerical models have been proposed for it, the effect of the environmental condition and particularly climate change has not been investigated with a region-specific perspective. The environmental parameters, such as temperature, relative humidity, and precipitation, have changed because of climate change effects. The variation of environmental

parameters have several impacts on the occurrence of extreme events, such as scour and flooding. In addition, climate change is believed to affect the continuous deterioration of RC bridges through its impact on various environmental parameters. Therefore, it is necessary to study how the deterioration mechanisms will change under the expected climate change scenarios. The outcome of this effort can be implemented to predict the future condition of bridges more realistically. Therefore, the stakeholders can better plan for necessary maintenance and repair actions, which lead to an optimized bridge management system.

Comparing Artificial Neural Networks and Ordered-Probit Models for Forecasting Pavement Condition in New Mexico

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Authors:

Natalia Sanabria, University of New Mexico, nsanabria@unm.edu
Vanessa Valentin, University of New Mexico
Susan Bogus, University of New Mexico
Guohui Zhang, University of New Mexico
Elmira Kalhor, University of New Mexico

Abstract: The decision making process for allocating and scheduling maintenance and rehabilitation activities within a road network depends on reliable and effective methods to effectively predict pavement's performance over its service life. Recent studies have identified Probabilistic Neural Networks Model (PNNM) and Ordered-Probit Models (OPM) as reliable tools for predicting pavement behaviors. The objective of this study is to compare the prediction capabilities of each model in forecasting the pavement distress rate. Both models were developed using traffic data as the independent variables and pavement's distress rate as the dependent variable. Their performance was compared from the estimation results using a dataset of 5,888 observations collected in Northern New Mexico. The findings of this study suggest that PNNM can be more accurate for predicting distress rate than OPM and can be used as input for a variety of practices in pavement management including investment, design and rehabilitation policy. In addition, the models suggest that variables such as peak hour volume and single heavy commercial average volume are significant predictors of the distress rate for a pavement. Although both models have been proven effective and reliable in predicting pavement deterioration, there has not been a study comparing their performance. This study provides a better understanding in their performance when compared to each other. The application of reliable predictive models, such as the PNNM, facilitates the decision-making process.

Effective Modeling of Extended Service Life for Pavement Treatments

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Authors:

John Kiefer, Michigan Technological University
Tim Colling, Michigan Technological University, tkcollin@mtu.edu
Shelley Farrey, Michigan Technological University

Abstract: This study determines the state of capital preventive maintenance (CPM) treatments used by Michigan local agencies and the extended service life (ESL) gained by applying CPM treatments to asphalt pavements. Local agencies in Michigan have actively used CPM treatments to maintain their

asphalt pavements. Chip seals comprised the majority of CPM treatments used by the agencies in this study. According to the data collected, CPM treatments applied by local agencies provide at least four years of ESL on average, which is consistent with studies conducted at the Michigan Department of Transportation (MDOT) and outside the state. Data analysis has been restricted to distresses found in asphalt pavement, which is the primary pavement type owned by Michigan local agencies. This study shows that local agencies have the tools and data to analyze the ESL of their CPM treatments and that chip seal treatment yields a positive ESL. Further research is needed on the statistical significance of other CPM treatments and for making regional assessments.

Migration Probability Matrix for Bridge Element Deterioration Models
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Author:

Paul D. Thompson, pdt@pdth.com

Abstract: Transportation agencies are required in 23 USC 119(e) to develop Transportation Asset Management Plans featuring life cycle cost analysis for bridges. Proposed regulations in 23 CFR 515.007 elaborate that this analysis and related bridge management systems must contain deterioration models. Element level bridge inspection data suitable for deterioration models have been collected by most State Departments of Transportation (DOTs) since the mid-1990s, but AASHTO in 2013 significantly modified the inspection process. FHWA has proposed adding the modified inspection language to the National Bridge Inventory in compliance with element inspection requirements in 23 USC 144(b). This presents a serious problem for all DOTs because none yet have sufficient element inspection data under the 2013 AASHTO manual to support deterioration modeling. Research completed in 2016 for the Florida Department of Transportation (FDOT) suggests one readily implementable solution to this problem. A migration probability matrix was developed to encapsulate the differences in definitions between Florida's bridge element inspection data gathered under AASHTO's 1998 Guide to Commonly-Recognized (CoRe) Structural Elements, and the new 2016 FDOT inspection manual, which is based on the 2013 AASHTO Manual for Bridge Element Inspection. Deterioration models previously developed using the older data can be easily multiplied by this migration probability matrix to develop reasonable models that are compatible with inspection data gathered under the new manual. Ultimately this migration matrix can be validated and improved once sufficient element inspection data are gathered under the new manual.

Modeling Pavement Condition and Deterioration: A Linear Empirical Bayes Approach
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Authors:

Samer W. Katicha, Virginia Tech Transportation Institute, skaticha@vt.edu
Gerardo W. Flintsch, Virginia Tech Transportation Institute
Brian Diefenderfer, Virginia Transportation Research Council

Abstract: We propose a linear empirical Bayes approach to estimate pavement condition and deterioration for the Virginia Department of Transportation (VDOT) Critical Condition Index (*CCI*). The approach consists of 1) fitting a pavement deterioration model as a function of pavement age and structural condition to the network *CCI* data and 2) estimating the pavement condition as a weighted average of the fitted model and the actual observed condition. This two steps approach of estimating

the model from the data and combining the observation and the model is the characteristics of an empirical Bayes approach. The approach assumes that the distribution of the pavement deterioration can be approximated by an adjusted Poisson-Gamma (negative binomial) model with the adjustment applied to take into account that the estimated error in the recorded/measured pavement condition is higher than what is predicted by the Poisson distribution. The approach is validated by showing that it improves the prediction of the future *CCI*, calculated using leave one out cross validation, by 21.6%.

Prediction Model of Concrete Girder Bridge Deterioration in Shanghai Using Weibull-Distribution Method

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Authors:
    Yu Fang, Tongji University, 1610049@tongji.edu.cn
    Li Li, Tongji University
    Zhang Chen, Tongji University
    Lijun Sun, Tongji University

Abstract: The bridge management system (BMS) in Shanghai has been applied to urban bridge management since 2004, and now over 2300 bridges across the city inspected annually. The prediction model of bridge deterioration is important for maintenance decision making, while most of existing methods such as regression or Markov chains are limited in prediction accuracy or not easy to use. In this paper, the overall condition of all bridges in Shanghai is analyzed, and the process method of historical data in the BMS database is given. Based on the assumption that the duration of bridge stays at each condition rating (CR) is a random variable, a prediction model of concrete girder bridge deterioration using Weibull distribution method is described. The parameters of Weibull distribution are obtained by fitting the inspected durations, then the calculation methods of bridge service-life behaviors such as the failure rate, reliability function, mean duration, or quantile statistics are also given. The predicted result of the deck system, superstructure, substructure, and whole bridge's deterioration using this approach shows that the duration of concrete girder bridge at each CR in Shanghai is about 15 years, and the service life of the bridge is generally no more than 70 years. By comparing the prediction results of three major components, it can be found that the superstructure is most easily damaged and the maintenance quality of superstructure still needed to be improved.

Personnel and Training

Cyber-Physical Systems Related to Historic Infrastructure Maintenance

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Authors:
    Lauren Gomez, University of New Mexico
    Shreya Vemuganti, University of New Mexico
    Fernando Moreu, University of New Mexico, fmoreu@unm.edu

Abstract: Overseas transportation systems across the world require a deeper understanding of maintenance and retrofit. As a result, European and other historic societies have a longer tradition on

maintaining their transportation infrastructure. However, because of their expertise in the subject, their understanding of transportation maintenance is approached using traditional, historic, and sometimes obsolete methods. Appreciation of historic transportation systems, their maintenance, and exposure to new technologies in engineering can bridge opportunities to undergraduate students interested in transportation research. This paper describes two courses exposing undergraduate students to both historic infrastructures and new cyber-physical systems adapted to civil engineering. The main focus is a recent experience at the University of New Mexico (UNM) with a study abroad class and a class designed under the Science, Technology, Engineering and Mathematics (STEM) program. The experiences learned will be applied to larger applications, to other institutions and professional areas, both in the US and internationally. The knowledge gained in the UNM STEM class will be related in the exposure to European transportation systems. The paper discusses the use of drones and internet for remote sensing and monitoring for transportation infrastructure maintenance. This exposure to design of new cyber-physical systems includes the vision of using remote sensing techniques to connect to the physical world through internet and data. Finally, this paper also gives a brief overview of the role of technology in engineering and how this can help to educate undergraduate engineers to design improved monitoring methods for existing infrastructure.

Modeling Long Term Highway Staffing Requirements for State Transportation Agencies
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Authors:
    Ying Li, University of Kentucky, ying.li@uky.edu
    Timothy R.B. Taylor, University of Kentucky
    Gabriel B. Dadi, University of Kentucky
    Roy E. Sturgill, University of Kentucky

Abstract: State Transportation Agencies across the country continue to face many challenges to repair and enhance highway infrastructure to meet rapidly increasing transportation needs. One of these challenges is maintaining an adequate and efficient agency staff. In order to effectively plan for future staffing levels, State Transportation Agencies need a method for forecasting long term staffing requirements. However, current methods in use cannot function without well-defined projects therefore making long term forecasts is difficult. This work seeks to develop a dynamic model which captures the feedback mechanisms within the system that determines highway staffing requirements. The system dynamics modeling methodology was used to build the forecasting model. The formal model was based on dynamic hypotheses derived from literature review and interviews with transportation experts. Both qualitative and quantitative data from literature and federal and state databases were used to support the values and equations in the model. The model integrates State Transportation Agencies' strategic plans, funding situations and staffing strategies while determining future staffing levels, and will hopefully fill the absence of long-term forecasting tools at State Transportation Agencies. The model was tested using standard system dynamics validation procedures, after which the model was calibrated using input data specific to the Kentucky Transportation Cabinet to simulate an expected retirement wave and search for solutions to address temporary staffing shortages.