Maintenance Management 2009

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Maintenance Management 2009

Presentations from the 12th AASHTO–TRB Maintenance Management Conference

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Preface

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

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

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Contents

MAINTENANCE QUALITY ASSURANCE

Use of Monte Carlo Simulation to Evaluate the Kansas Department of Transportation’s Maintenance Quality Assurance Program (MMC09-042) ........................................3
Steven D. Schrock, C. Bryan Young, and Deepak Chellamani

Development of a Comprehensive Framework for the Efficiency Measurement of Road Maintenance Strategies Using Data Envelopment Analysis (MMC09-032) .............19
Mehmet E. Ozbek, Jesús M. de la Garza, and Konstantinos Triantis

Maintenance Quality Assurance in North America:
State of the Practice (MMC09-030A) .................................................................................33
Teresa Adams, Jason Bittner, Will Sierzchula, and Jennifer Brandenburg

PERFORMANCE-BASED CONTRACTING AND ASSET MANAGEMENT

North Carolina Department of Transportation’s Performance-Based Contracting Experience in Charlotte (MMC09-005) ........................................................................................................37
Jonathan Arnold, Jennifer Brandenburg, and Lonnie Watkins

Performance-Based Contracting—Yes or No: An In-Depth Analysis (MMC09-002) .........49
Bob G. McCullouch and Panagiotis Ch. Anastasopoulos

Results and Lessons Learned from District of Columbia Department of Transportation’s Tunnel Asset Management Contract (MMC09-015A) ........................................65
Pekka Pakkala, Mark Robinson, Simon Rennie, and Yared Tesfaye

BRIDGE MONITORING AND PLANNING

Asset Management Plan for the Ambassador Bridge (MMC09-025) ........................................69
Michael F. Britt and Michael J. Borzok

A Wireless Sensor for Monitoring Chloride Ingress in Concrete (MMC09-028) ....................87
Rengaswamy Srinivasan, Bliss G. Carkhuff, Terry E. Phillips, and Hassan M. Saffarian

PAVEMENT PERFORMANCE AND PRESERVATION PROGRAMS

Long-Term Performance of Failed Flexible Pavements Stabilized with Cement (MMC09-021) ........................................................................................................101
Gregory E. Halsted

Concrete Pavement Preservation and Rehabilitation to Meet Sustainability Demands (MMC09-036) ..........................................................................................117
Dale S. Harrington, Kurt D. Smith, John Roberts, and Marcia Brink

Implementation of a Pavement Preservation Program in Illinois (MMC09-043) ..................137
Angela Wolters, David Peshkin, LaDonna Rowden, and Kevin Burke III
OUTSOURCING AND SAFETY ISSUES

Outsourcing: What Are You Prepared to Do About It? (MMC09-009A) ............................155
  Marshall Stivers
Pavement Striping Visibility in Wet Conditions (MMC09-018A) .................................157
  Vincent Liu
Variable Speed Limit Signs: Effects on Speed and Speed Variation in Work Zones (MMC09-008) .................................................................159
  Thomas McMurtry, Matt Riffkin, Suellen Heath, and Mitsuru Saito

MANAGEMENT SYSTEMS: DATA COLLECTION, MAXIMIZING RESOURCES, AND PAVEMENT KNOWLEDGE BASE

Use of PDAs to Capture Field Data for Input in North Carolina’s Maintenance Management System (MMC09-022) .............................................................177
  Jim Edgerton, Charles Pilson, and Matthew Whitley
Maximizing Resource Use to Meet the Maintenance Management Challenge: As Demonstrated by Traffic Signal Maintenance Management in the City of Norfolk, Virginia (MMC09-023) .................................................................191
  Lonnie H. Tebow
Pavement Management System: From Database to Knowledge Base (MMC09-029A) ..................................................................................................................207
  Wenbing Song

WORKFORCE DEVELOPMENT

Transportation Supervisor Workforce Development for the North Carolina Department of Transportation (MMC09-024) .................................................................211
  Scott G. Capps and Kevin Brantley

MANAGEMENT ASPECTS OF WINTER SERVICES

Cost–Benefit Analysis of the Pooled-Fund Maintenance Decision Support System: Case Studies (MMC09-020) .................................................................229
  Zhirui Ye, Xianming Shi, and Christopher K. Strong
Integrating Maintenance Management Systems with Maintenance Decision Support Systems (MMC09-048) .................................................................245
  Paul A. Pisano, William H. Hoffman, and Andrew D. Stern
Use and Cost–Benefit of Weather Information in Winter Maintenance (MMC09-019) .....255
  Zhirui Ye, Xianming Shi, and Christopher K. Strong
ENVIRONMENTAL ASSETS, VEGETATION INVENTORY, AND MAINTENANCE ISSUES IN DESIGN AND CONSTRUCTION

Management of Environmental Features and Assets (MMC09-047) ...........................................269
Marie Venner and Christine Paulsen

State Department of Transportation Vegetation Inventory Protocol Project (MMC09-026A)..............................................................................................287
Victor Maddox, Clifton Abbott, John Byrd, Jr., and Dave Thompson

Solving Maintenance Issues in Design and Construction (MMC09-013).........................289
Joe S. Graff

APPENDIX: Author Contact Information..............................................................................303
Maintenance Quality Assurance
MAINTENANCE QUALITY ASSURANCE

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

MEHMET E. OZBEK
Colorado State University

JESÚS M. DE LA GARZA
Konstantinos Triantis
Virginia Tech

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

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

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

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

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

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

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

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

DATA ENVELOPMENT ANALYSIS

A commonly used measure of efficiency (8) is

\[ \text{Efficiency} = \frac{\text{Output}}{\text{Input}} \]  

(1)

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

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

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

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

Figure 1 presents the application of DEA for a process with two inputs and a single output. For example, let’s assume that the process under investigation is the road paving operation. The inputs of the process are: (a) the number of paving crews ($x_1$) and (b) the time spent in days for the paving operation ($x_2$). The output of the process is lane miles of road paved ($y$). The DMUs (e.g., different contractors undertaking this paving operation) shown in dots, are plotted on an $x$–$y$ plane by using the values for their inputs ($x_1$ and $x_2$) and output ($y$). Then, the efficient frontier, containing the DMUs with 100% efficiency score (relative to the other DMUs in the data set), is drawn by identifying the efficient pairs. Efficient pairs are identified by picking adjacent pairs of DMUs and connecting them with a line segment. If the line segment has a non-positive slope and none of the other DMUs lies between such line segment and the origin, then chosen DMUs are stated to be efficient and otherwise they are stated to be inefficient (14). Hence, according to Figure 1, DMUs represented by “E,” “D,” “C,” and “F” have an efficiency score of 100%, and DMUs represented by “A” and “B” have efficiency scores that are between 0% and 100%. The efficiency score for any inefficient DMU can be calculated by measuring its relative distance from the efficient frontier. For example, the efficiency score of DMU B can be identified to be 63% by computing the ratio of $|OB|'$ to $|OB|$ as shown in Figure 1. It is important to note that DEA not only identifies the efficiency score for each DMU but also
FIGURE 1 DEA model for a process with two inputs and a single output (8).

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

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

\[
\begin{align*}
\text{maximize } Q_0 &= \frac{\sum_{i=1}^{m} u_r y_{r0}}{\sum_{i=1}^{m} v_i x_{i0}} \\
\text{subject to } &\sum_{r=1}^{s} u_r y_{rj} \leq 1 ; j = 1, \ldots, n; r = 1, \ldots, s; i = 1, \ldots, m
\end{align*}
\]
where

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

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

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

STRENGTHS AND LIMITATIONS OF DATA ENVELOPMENT ANALYSIS

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

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

The most important limitations of DEA are as follows (9, 16, 17):
• Application of DEA requires a separate linear program be solved for each DMU in the data set. When there are many DMUs, the computation can be cumbersome. Nonetheless, this limitation has been minimized with the development of computer software that specifically deals with DEA problems.
• Since DEA is an extreme point technique, errors in measurement or recording of data for input-output variables may result in significant problems. Thus, utmost care should be given to assure that input-output data is accurate.
• As efficiency scores in DEA are obtained by running a series of linear program formulations, it becomes intuitively difficult to explain the process of DEA to the nontechnical audience or decision makers for the cases in which there are more than two inputs and outputs. An audience that does not have background in linear programming may not deem DEA as transparent and may find it difficult to comprehend its results. Nonetheless, this issue may be overcome by explaining the DEA process in simpler terms and by proper use of charts and tables to communicate the results.
• DEA cannot deal with qualitative variables. Such variables need to be assigned numerical values to be used in the mathematical evaluation of efficiency as used in DEA. The common practice to perform this is to find some measurable surrogate variable which possesses a known relation to the varying levels of the qualitative variable.

ROAD MAINTENANCE EFFICIENCY MEASUREMENT FRAMEWORK

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

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

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

---

Decide on the size of the DMU

---

Address the issue of uncontrollable factors

---

Refine the comprehensive list of input-output variables and uncontrollable factors

---

Prepare the data to be used in the DEA models

---

Perform data mining

---

Clean the data

---

Allocate the data to the DMUs

---

Choose the type of DEA models to be run

---

Perform data conversion and data rearrangement

---

Run the DEA models and obtain the efficiency score, targets, and peer(s) for each DMU; and the overall efficient frontiers

---

Derive overall conclusions (such as the reasons of inefficiency, benchmarks, best practices) that would help the decision-making process

---

: Denotes the framework’s component number.

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

---

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

<table>
<thead>
<tr>
<th>Variable Name</th>
<th>Variable Explanation or Metric</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost for maintaining the bridges</td>
<td>Dollars</td>
</tr>
<tr>
<td>Climate: effect on deterioration of the bridges</td>
<td>Yearly temperature cycles (Δ temperature), number of yearly freeze–thaw cycles</td>
</tr>
<tr>
<td>Climate: effect on maintenance efforts performed for meeting level-of-service requirements for the bridges (productivity–availability of crews)</td>
<td>Yearly precipitation amounts (inches)</td>
</tr>
<tr>
<td>Traffic: effect on deterioration of the bridges</td>
<td>Equivalent Single Axle Load (ESAL)</td>
</tr>
<tr>
<td>Traffic: effect on maintenance efforts performed for meeting level-of-service requirements for the bridges (productivity–availability of crews)</td>
<td>Average daily traffic (ADT)</td>
</tr>
<tr>
<td>Snow treatment: effect on deterioration of the bridges</td>
<td>Count (of chloride applications)</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Variable Name</th>
<th>Variable Explanation or Metric</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Variables and Uncontrollable Factors</td>
<td></td>
</tr>
<tr>
<td>Speed limit: effect on deterioration of the bridge</td>
<td>Miles per hour</td>
</tr>
<tr>
<td>Accidents damaging bridges: effect on deterioration of the bridges</td>
<td>Count (of accidents damaging bridges) per year</td>
</tr>
<tr>
<td>Subsurface conditions: effect on deterioration of the bridges</td>
<td>Good, poor, rock soil, water table, etc. (give a grade based on effect)</td>
</tr>
<tr>
<td>Thickness of the deck: effect on deterioration of the bridges</td>
<td>Inches</td>
</tr>
<tr>
<td>Type of paved lanes: effect on deterioration of the bridges</td>
<td>Concrete, asphalt (give a grade based on the effect)</td>
</tr>
<tr>
<td>Type of paved lanes: effect on maintenance efforts performed for meeting level-of-service requirements for the bridges (productivity of crews)</td>
<td>Concrete, asphalt (give a grade based on the effect)</td>
</tr>
<tr>
<td>Span information: effect on deterioration of the bridges</td>
<td>Span length, span type, etc.</td>
</tr>
<tr>
<td>Age of bridges: effect on deterioration of the bridges</td>
<td>Years</td>
</tr>
<tr>
<td>Location: effect on deterioration of the bridges</td>
<td>Above a creek, major river, highway, railroad, etc. (give a grade based on effect)</td>
</tr>
<tr>
<td>Location: effect on maintenance efforts performed for meeting LOS requirements for the bridges (productivity of crews)</td>
<td>Above a creek, major river, highway, railroad, etc. (give a grade based on effect)</td>
</tr>
<tr>
<td>Terrain: effect on deterioration of the bridges</td>
<td>Slope, elevation, and orientation</td>
</tr>
<tr>
<td>Terrain: effect on maintenance efforts performed for meeting LOS requirements for the bridges (productivity of crews)</td>
<td>Slope, elevation, and orientation</td>
</tr>
<tr>
<td>Total area served: effect on maintenance efforts performed for meeting LOS requirements for the bridges (productivity of crews)</td>
<td>Sum of the area (deck length × deck width) of all of the bridges within the DMU</td>
</tr>
<tr>
<td>Output Variables</td>
<td></td>
</tr>
<tr>
<td>Change in the condition of the deck of the bridge</td>
<td>Deck rating(<em>{t1}) – deck rating(</em>{t0})</td>
</tr>
<tr>
<td>Change in the condition of the superstructure of the bridge</td>
<td>Superstructure rating(<em>{t1}) – superstructure rating(</em>{t0})</td>
</tr>
<tr>
<td>Change in the condition of the substructure of the bridge</td>
<td>Substructure rating(<em>{t1}) – substructure rating(</em>{t0})</td>
</tr>
<tr>
<td>Change in the condition of the slope/channel protection of the bridge</td>
<td>Slope/channel protection rating(<em>{t1}) – slope/channel protection rating(</em>{t0})</td>
</tr>
<tr>
<td>Air pollution</td>
<td>Emission amounts</td>
</tr>
<tr>
<td>Water pollution</td>
<td>Emission amounts</td>
</tr>
<tr>
<td>Noise pollution</td>
<td>Emission amounts</td>
</tr>
</tbody>
</table>
**Component 2: Deciding on the Size of the DMU**

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

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

**Component 3: Addressing the Issue of Uncontrollable Factors**

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

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

**Component 4: Refining the Comprehensive List of Variables**

Running the DEA model using a large number of variables (as the ones shown in Table 1) would shift the compared DMUs towards the efficient frontier, resulting in a large number of DMUs to have high efficiency scores. The reason for this is as DEA allows flexibility in the choice of input-output variables’ weights, the greater the number of variables included in the analysis, the lower the level of its discrimination. A DMU for which one particular ratio of an output to an input is the highest can allocate all of its weight to this ratio and become efficient. The total number of such ratios will be the product of the number of inputs and outputs. This product is a practical indicator of the minimum number of efficient units that will result from the implementation of DEA. Thus, in a case with four inputs and four outputs, DEA would result in at least 16 efficient DMUs. A suggested rule of thumb to achieve a reasonable level of discrimination is that the number of DMUs should be at least $2 \times m \times t$ where $m \times t$ is the product of the number of inputs and number of outputs (20, 21). Therefore, once the initial comprehensive list of variables is developed, such list needs to be reinvestigated and refined to be able to increase the discriminating power of the DEA models. Such refinement can be performed by means of a variety of approaches such as analytic hierarchy process, regression analysis, and principal component analysis (18).
Component 5: Preparation of the Data to Be Used in the DEA Models

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

Component 6: DEA Model Selection

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

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

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

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

Component 7: Running the DEA Model to Obtain the Results

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

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

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

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

CONCLUSIONS

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

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

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

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

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REFERENCES


