Data and Modeling Issues Faced during the Efficiency Measurement of Road Maintenance Using Data Envelopment Analysis

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Abstract: Within the past two decades, the road maintenance concept has been gaining tremendous attention. This has brought about new institutional changes, predominant of which is the challenge for maintenance managers to achieve maximum performance from the existing road system. Such challenge makes it imperative to implement comprehensive systems that measure road maintenance performance. However, as pointed out by the Transportation Research Board, even though the road maintenance performance measurement systems developed and implemented by the state departments of transportation elaborate on the maintenance level of service (i.e., effectiveness of the road maintenance), the fundamental relationships between the maintenance level of service and the budget requirements (i.e., efficiency of road maintenance) need more investigation. This is mainly because not knowing how "efficient" state departments of transportation are in being "effective" can lead to excessive and unrealistic maintenance budget expectations. In an effort to address this need, this research aims to develop and implement a comprehensive framework that can measure the overall efficiency of road maintenance operations. This framework is designed to consider the effects of environmental (e.g., climate, location, etc.) and operational (e.g., traffic, load, etc.) factors on such overall efficiency. This paper introduces the efficiency measurement framework and specifically provides an overview of the data and modeling issues faced during the early stages of the implementation of the framework to the Virginia Department of Transportation's case for the maintenance of bridges.

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Introduction

Within the past two decades, the road maintenance concept has been gaining tremendous attention. The main reason for this is the fact that with the construction of the interstate system essentially completed, the focus of transportation programs has been moving from capital investment to maintenance and operation. As infrastructure building is slowing down, the maintenance of the existing infrastructure is becoming much more critical. From the early 1990s, the U.S. federal government implemented a program of preservation, maintenance, and restoration. The Intermodal Surface Transportation Efficiency Act of 1991 established the interstate maintenance program which called for pavement, bridge, and other management systems to be implemented by the state departments of transportation (state DOTs) in an effort to preserve the current system and improve its efficiency (TRB 2006).

In 1988, a survey performed on about 10% of all the U.S. infrastructure by the National Council on Public Works Improvement (as appointed by the president of the United States) revealed that the nation's roads were in better than fair condition. A number of similar surveys were performed by the 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 past two decades (Mirza 2006).

The aforementioned phenomena bring about new institutional changes, predominant of which is the challenge for maintenance managers to achieve maximum performance from the existing system (TRB 2006). 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) (TRB 2006).

The Virginia Department of Transportation (VDOT) has been very active in road maintenance performance measurement. VDOT is in collaboration with the writers of this paper for the assessment of the performance-based road maintenance contracts it issues. Since 2000, the writers have been involved in performing research to identify innovative methodologies to measure the effectiveness of the road maintenance services undertaken by

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VDOT as well as the contractors working for VDOT under the terms of performance-based contracts. Within the context of such research, a framework has been developed to measure the performance of the road maintenance services with respect to the effectiveness of the following components: (1) level of service; (2) cost; (3) timeliness of response; (4) customer satisfaction; and (5) safety (Piñero 2003).

Other state DOTs are also implementing a variety of performance measurement systems focusing on the level of service obtained as a result of their road maintenance processes (TRB 2006). Furthermore, state DOTs seek to measure not only the "effectiveness" of their road maintenance processes (i.e., how good their outputs and outcomes are) but also the "efficiency" of—and value added through—such processes as far as the reduction in taxpayer costs, the reduction in user costs (e.g., travel time and accidents), and the reduction in undesirable outputs (i.e., air, noise, and water pollution) are concerned (TRB 2006).

Significance of the Problem

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 (Piñero 2003). In other words, effectiveness can be stated as "doing the right things" and efficiency can be stated as "doing the things right" (Drucker 1967). Obviously, in a road maintenance concept, everyone would want the actions (maintenance) to be effective, i.e., result in safe, smoother, and good quality roads. But it is also reasonable to assume that efficiency, i.e., spending less money, less time, etc., in performing road maintenance, is also of importance and thus needs to be accounted for. Road users, as tax payers, expect not only a well-maintained road system but also require it to be efficiently maintained (Dunlop 1999). Furthermore, as underlined by the Virginia General Assembly's Joint Legislative Audit and Review Commission, the asset management concept calls for the delivery of effective and efficient services to the community (JLARC 2002).

As pointed out by the Transportation Research Board (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 (i.e., effectiveness of the road maintenance), the fundamental relationships between the maintenance level of service and the budget requirements (i.e., efficiency of road maintenance) need more investigation (TRB 2006). This is mainly because 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.

In an effort to address this need, this research aims to develop and implement a comprehensive framework that can measure the overall efficiency of road maintenance operations. This framework is designed to consider the effects of environmental (e.g., climate, location, etc.) and operational (e.g., traffic, load, etc.) factors on such overall efficiency. Considering the effects of such uncontrollable factors is very important in any maintenance performance measurement system, especially for the instances in which comparative analyses are made (which is the case for this research, as will be discussed later on). This is mainly because disregarding the 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.

This paper introduces the road maintenance efficiency measurement framework and specifically provides an overview of the data and modeling issues faced during the early stages of the implementation of the framework to the VDOT's case for the maintenance of bridges. It is important to note that the core implementation stages such as the data preparation, model runs, results, validation, and implications on decision making are not discussed in this paper and is the subject of another paper (Ozbek et al. 2010).

Point of Departure

A commonly used measure of efficiency is (Cooper et al. 1999)

$$\text{Efficiency} = \text{Output/Input} \tag{1}$$

This measure is often inadequate due to the existence of multiple inputs and outputs in complex processes. A review of literature has identified the following five approaches that can be used to measure and compare the efficiencies of processes with multiple inputs and/or outputs. However, as discussed under their respective headings, each of the first four approaches has some shortcomings as far as its applicability to this research is concerned.

- Partial efficiency measure approach: this approach requires investigating and calculating the single output to single input ratio shown in Expression (1) one at a time for each relevant input and output (Sexton 1986). One major drawback of this approach is its potential to result in serious misunderstanding about the overall efficiency of a process when only a single partial efficiency ratio (of possible many ratios) is used to determine the overall efficiency of such process (Craig and Harris 1973). Even if all of the possible partial efficiency ratios are computed for a process, it is very challenging to reach definitive conclusions about the overall efficiency of that process especially when such ratios are used to compare the efficiencies of different units. This is mainly because one partial efficiency ratio may suggest that a unit is performing better than another and another partial efficiency ratio may suggest just the opposite, preventing the decision maker from reaching definitive conclusions about the overall efficiency of the units. To understand this issue, let us focus on the guardrail maintenance process performed in a section of a highway. The inputs used for that process (material, labor, and equipment) can be stated in terms of the amount of expenditures (this results in one combined input). The process yields to "maintained guardrails" and the effectiveness of the process can be stated in terms of two main output measures. The first output measure is the level-of-service score. This level-of-service score represents the percentage of guardrails that meet preestablished maintenance criteria such as (1) being free of rust that would affect the structural integrity; (2) being free of dents that would affect the structural integrity; and (3) meeting the height requirements, etc. The second output measure is the timeliness-of-response score. This timeliness-of-response score represents the percentage of the guardrail repairs that were completed in a preestablished time frame. Since guardrail is of paramount importance for the safety of the road users, state DOTs typically require that the repair or replacement of the guardrail that lost its structural integrity is performed within 48 h of the time it is damaged. In this example, the overall efficiency of the guardrail maintenance process cannot be measured by using the basic efficiency ratio shown in Expression (1) since there are two outputs and a single input.

- Total factor efficiency measure approach: this approach derives an output-to-input measure that takes into account all of the inputs and outputs at one time. Even though total factor efficiency measure is essential to cover all variables (inputs and outputs) that are associated with a process at one time (overcoming the problem inherent in partial efficiency measure approach), it has one major drawback. It requires that the decision maker prescribes weights to each input and output variables to obtain a ratio that reduces to a form like the one in Expression (1) (Cooper et al. 1999). Since this is a task that could result in different weights to be chosen by different individuals, this approach is very likely to have biased results.
- System dynamics: system dynamics is an approach to understand, model, and simulate the dynamic behavior of complex systems/processes. This approach models a problem that manifests itself dynamically over time by capturing important feedback mechanisms. This approach acknowledges that systems are vastly affected by the environment in which they exist (Sterman 2000). A major advantage of the system dynamics approach is its ability to capture the temporal impacts of decisions. While the aforementioned approaches can measure the efficiency of a system at a given time by investigating the inputs and outputs of that system at such time, the system dynamics approach can explore how the changes in inputs and outputs impact efficiency performance over time (Chasey et al. 1997; Vaneman and Triantis 2007). The main disadvantage of this approach (as far as its applicability to this research is concerned) is the fact that it requires the definition of the structure (physical, decision making, and organizational) of the maintenance process. To do so presupposes the ability to define the mathematical relationships between key variables. For a complex process with many variables (like the road maintenance process), obtaining the necessary mathematical relationships is most challenging and requires a significant amount of participation from the decision makers of the process that is being modeled.
- Regression analysis: this approach suggests that by using the input and output data for units under investigation one can perform regression analysis to identify a parametric equation (linking inputs to outputs) that models the process under investigation. This average relationship (which can be used to calculate the expected output level of a unit given its input level) is assumed to apply to each unit that is being compared within the data set. Units which produce more output than what the model predicts are relatively more efficient than the units which produce less output than what the model predicts. The main shortcoming of this approach is the fact that it compares the efficiency of units against a hypothetical average performance (i.e., line depicted by the equation obtained through regression), not against the best performance in the data set (Charnes et al. 1994; Sexton 1986).
- Data envelopment analysis (DEA): DEA, which was initially proposed by Charnes et al. in their 1978 seminal paper (Charnes et al. 1978), is an approach that can deal with processes that have multiple inputs and/or multiple outputs and yet does not possess the shortcomings of any of the aforementioned approaches. DEA is a mathematical method based on the 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 (Ramanathan 2003; Silkman 1986). 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 (Silkman 1986). The weights used are DMU specific and during the application of DEA they are optimized by each DMU to maximize its own efficiency rating. 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% for any of the DMUs in the data set (Sexton 1986; Thanassoulis 2001). The weights for the inputs and outputs do not need to be identified by the decision maker and instead they are determined and optimized by the DEA model in the best interest of DMUs (Thanassoulis 2001).

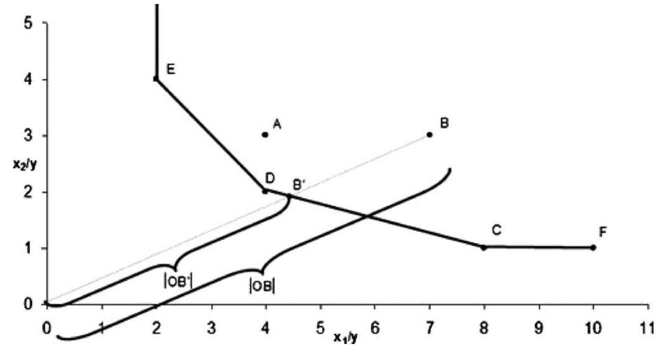

Fig. 1. DEA model for a process with two inputs and a single output [adapted from Cooper et al. (1999, p. 28)]

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 0–100% (de la Garza et al. 2005). Fig. 1 presents the application of DEA for a process with two inputs and a single output. The DMUs, 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 nonpositive slope and none of the other DMUs lies between such line segment and the origin then the chosen DMUs are determined to be efficient, otherwise they are stated to be inefficient (Triantis 2005). Hence, according to Fig. 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, efficiency score of DMU B can be identified to be 63% by computing the ratio of $|OB'|$ to $|OB|$, as shown in Fig. 1. It is important to note that DEA not only identifies the efficiency score for each DMU but also identifies the peer DMUs for inefficient DMUs. For the example presented in Fig. 1, the peer DMUs for DMU B can be identified as DMU C and DMU D as the projection of

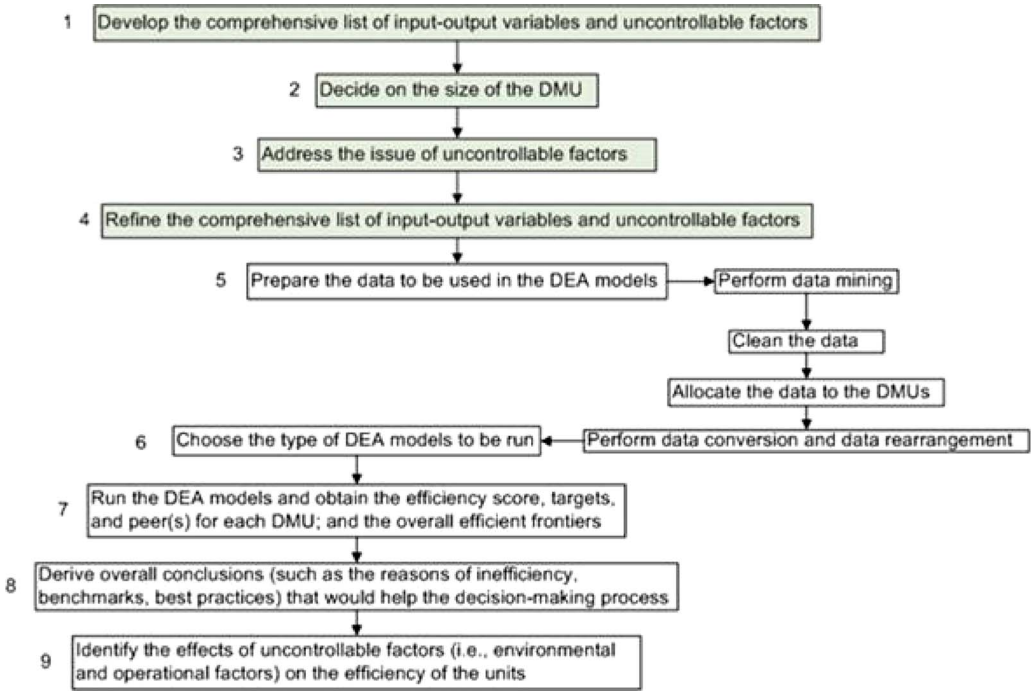

Fig. 2. Components of the developed framework and the focus of this paper

DMU B on the efficient frontier, B', is a weighted combination of such peer DMUs.

Given the fact that DEA does not possess the shortcomings of any of the efficiency measurement approaches discussed earlier, it is chosen to be the approach to be used for the development of the road maintenance efficiency measurement framework.

Some of the important limitations of DEA are discussed briefly below (Golany and Roll 1989; Ramanathan 2003; Rouse 1997). Another limitation will be discussed later in this paper. For a complete discussion on the limitations of DEA, the reader is referred to Ozbek (2007).

1. Application of DEA requires a separate linear program to be solved for each DMU in the data set. When there are many DMUs, the computation can be cumbersome.
2. 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 are accurate.
3. 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 and/or decision makers for the cases in which there are more than two inputs and outputs.
4. DEA cannot deal with qualitative variables. Such variables need to be assigned numerical values that can be used in the mathematical DEA evaluation of efficiency. A common practice to deal with this issue is to find some measurable surrogate variable which possesses a known relation to the varying levels of the qualitative variable.

DEA Modeling Issues

As mentioned earlier, the purpose of this paper is to provide an overview of the data and modeling issues faced during the early stages of the implementation of the developed DEA efficiency measurement framework to the case of VDOT. Before doing so, it is important to list the components of the developed framework. Fig. 2 presents the components of such framework. This paper focuses on the data and modeling issues relevant only to the first four components (as highlighted in Fig. 2) as Component 5 and onward pertain to the core implementation stages of the framework that are discussed in a companion paper (Ozbek et al. 2010).

Development of the Comprehensive List of Input-Output Variables and Uncontrollable Factors (Component 1)

Overview of the Road Maintenance Process

Greitzer defines the highway maintenance as "*the act of preserving and keeping a highway, including all of its elements, in condition as close as is practical to its originally constructed condition, or its subsequently improved condition; and the operation of a highway facility and services incidental thereto, to provide safe, convenient, and economical highway transportation.*" (Greitzer 1976, p. 59). Greitzer divided the road maintenance into two main activities as physical maintenance and traffic services/operations (Greitzer 1976). In Virginia, the accepted types of road maintenance are (JLARC 2002; Ozbek 2004; VDOT 2005):

- Preventive maintenance: this type of maintenance consists of activities that are performed to extend the life of newly constructed asset items. Such activities are performed in a planned fashion and in advance of a need for repairs and in advance of substantial deterioration of the asset items to be able to avoid such occurrences, to decrease the deterioration rate of such asset items, to increase the time in which they become defective, and to maintain or improve the overall functional condition of the road system without enhancing its structural capacity. Preventive maintenance is (1) planned; (2) cyclical; (3) not condition based; and (4) not performed to add structural capacity (where applicable, e.g., pavement).

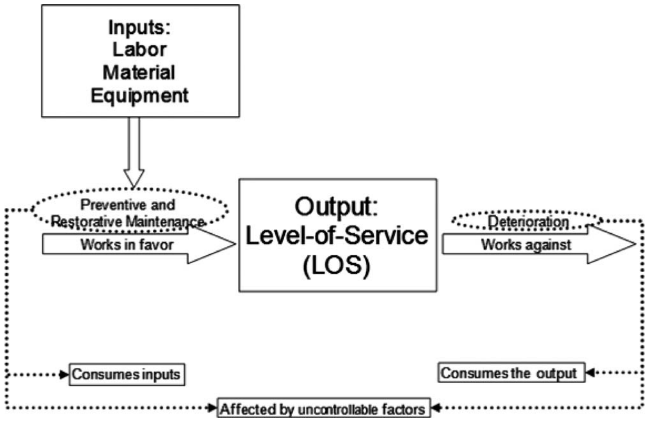

Fig. 3. Effects of various phenomena on the level of service

- Restorative (reactive) maintenance: this type of maintenance consists of activities that are performed to return an asset item as close as possible to its original condition. This requires minor repairs and replacement of certain components. Such maintenance is performed on asset items that are still functioning and structurally sound but which have minor defects such as section loss, cracking, etc.
- Rehabilitative maintenance: this type of maintenance consists of major repairs and replacements. Such efforts are regarded as reconstructions which are much more expensive than the aforementioned two types of maintenance. It is important to note that rehabilitative maintenance is disregarded within this research as it is more like construction rather than maintenance.

By using the definitions of the physical maintenance types, as discussed above, one can identify the effects of various phenomena on the level of service. Such relationships are shown in Fig. 3.

Defining Input-Output Variables

This research deals with all asset items present within the right-of-way fences (e.g., concrete barriers, shoulders, ditches, paved lanes, bridges, etc.). However, this paper focuses only on the DEA models developed for bridges (maintained by VDOT) to present the relevant data and modeling issues. As can be seen in Fig. 3, the inputs for the bridge maintenance process can be defined as labor, material, and equipment. Likewise, the output for such process is the generated level of service. The DEA technique relies on quantifiable measures to be able to compute efficient frontiers. Therefore all variables should be quantified using some metrics. As far as input variables are concerned, such metrics are labor hours, quantity of material, and equipment hours. All of these metrics can in turn be represented in terms of the cost associated with them. On the output side, an objective metric which can depict the level of service with respect to bridges is the national bridge inventory (NBI) rating which is gathered through a Federally mandated data collection program.

Defining Uncontrollable Factors

It is important to note that Fig. 3 depicts only the variables (inputs and the output) that are controllable by the decision maker. The DEA approach is also able to take the uncontrollable factors which are not shown in Fig. 3 into consideration. This, indeed, ensures a fair comparison to be made as uncontrollable factors such as environmental (i.e., climate, location, etc.) and operational (i.e., traffic, load, etc.) factors which greatly affect the maintenance efforts performed for the bridges as well as affecting the deterioration of the bridges.

Road maintenance is a process that is greatly affected by the uncontrollable factors. The reviewed literature lists the major uncontrollable factors as (1) climatic conditions; (2) traffic volume; (3) characteristic of the traffic that travels on the road; (4) geographic location; (5) terrain; (6) age of the road; (7) type or class of the road (e.g., pavement types); (8) the road's surrounding environment; (9) road design (e.g., type of materials, thickness, etc.); (10) road construction (e.g., quality of materials and workmanship, conditions during the construction phase, etc.); (11) subsurface conditions; and (12) amount of snow and ice treatment applied to the road (Caltrans 1998; de la Garza et al. 1998; Greitzer 1976; JLARC 2002; TRB 1997).

It is essential to identify the primary goal of a process to be able to figure out the uncontrollable factors affecting such process. Once such goal is identified, the phenomena that work in the favor of and against such goal need to be listed. Each of these phenomena can be affected by some factors that are beyond the immediate control of the decision maker. For the bridge maintenance process, the primary goal is to generate a sufficient level of service. Fig. 3 portrays the two phenomena that work in the favor of and against such goal. Thus, there are two groups of uncontrollable factors: (1) uncontrollable factors that affect the preventive and restorative maintenance efforts and (2) uncontrollable factors that affect the deterioration.

Comprehensive List of Input-Output Variables and Uncontrollable Factors

One of the most important features of DEA is that it does not require the specification of a functional form. Therefore, any variable (i.e., input and output) can be included in the model without the need to specify functional or parametric relationships. Even a factor that is neither an economic resource nor a product but just an attribute of the environment or of the production process (i.e., uncontrollable factor) can easily be included as a variable in the DEA model. Moreover, DEA does not make a priori distinction between the relative importance of any input or any output. In other words, all variables that are included in the model have an equal opportunity to influence the computed efficiency (Epstein and Henderson 1989). Given this, the initial list of input-output variables and uncontrollable factors used to assess the efficiency of a DMU tends to be and, in fact, should be as comprehensive as possible. This list should contain each relevant and suitable input-output variables and uncontrollable factor which affect the efficiency of the DMUs and which are strongly related with the objectives of the DMUs.

In order to be able to develop the comprehensive list of input-output variables and uncontrollable factors, the process whose efficiency is measured has to be scrutinized. Specifically, the answers to the questions: "What does this process do?" "How does this process accomplish its activities?" "Which outputs does this process produce?" "Which inputs does this process use to produce its outputs?" "Which internal and external uncontrollable factors affect this process?" should continuously be sought during the development of this list.

The comprehensive list of input-output variables and uncontrollable factors pertinent to the maintenance of bridges has been developed by following the discussion presented in the "Overview of the Road Maintenance Process," "Defining Input-Output Variables," and "Defining Uncontrollable Factors" sections and by reviewing the literature related to the subject matter (Caltrans

Table 1. Comprehensive List of Input-Output Variables and Uncontrollable Factors Pertinent to the Maintenance of Bridges

Type	Name	Explanation and/or metric
Input variables and uncontrollable factors	1. Cost for maintaining the bridges	Dollars
	2. Climate—effect on deterioration of the bridges	Yearly temperature cycles (Δ temperature), number of yearly freeze-thaw cycles
	3. Climate—effect on maintenance efforts performed for meeting level of service requirements for the bridges (productivity/availability of crews)	Yearly precipitation amounts (in.)
	4. Traffic—effect on deterioration of the bridges	Equivalent single axle load
	5. Traffic—effect on maintenance efforts performed for meeting level of service requirements for the bridges (productivity/availability of crews)	Average daily traffic
	6. Snow treatment—effect on deterioration of the bridges	Count (of chloride applications)
	7. Speed limit—effect on deterioration of the bridges	Miles/hour
	8. Accidents damaging bridges—effect on deterioration of the bridges	Count (of accidents damaging bridges)/year
	9. Subsurface conditions—effect on deterioration of the bridges	Good, poor, rock soil, water table, etc. (give a grade based on effect)
	10. Thickness of the deck—effect on deterioration of the bridges	Inches
	11. Type of paved lanes—effect on deterioration of the bridges	Concrete, asphalt (give a grade based on the effect)
	12. Type of paved lanes—effect on maintenance efforts performed for meeting level of service requirements for the bridges (productivity of crews)	Concrete, asphalt (give a grade based on the effect)
	13. Span information—effect on deterioration of the bridges	Span length, span type, etc.
	14. Age of bridges—effect on deterioration of the bridges	Years
	15. Location—effect on deterioration of the bridges	Above a creek, major river, highway, railroad, etc. (give a grade based on effect)
	16. Location—effect on maintenance efforts performed for meeting level of service requirements for the bridges (productivity of crews)	Above a creek, major river, highway, railroad, etc. (give a grade based on effect)
	17. Terrain—effect on deterioration of the bridges	Slope, elevation, and orientation
	18. Terrain—effect on maintenance efforts performed for meeting level of service requirements for the bridges (productivity of crews)	Slope, elevation, and orientation
	19. Total area served—effect on maintenance efforts performed for meeting level of service requirements for the bridges (productivity of crews)	Sum of the area (deck length $\times$ deck width) of all of the bridges within the DMU
Output variables	20. Change in the condition of the deck of the bridge	Deck rating$_{t1}$ − deck rating$_{t0}$
	21. Change in the condition of the superstructure of the bridge	Superstructure rating$_{t1}$ − superstructure rating$_{t0}$
	22. Change in the condition of the substructure of the bridge	Substructure rating$_{t1}$ − substructure rating$_{t0}$
	23. Change in the condition of the slope/channel protection of the bridge	Slope/channel protection rating$_{t1}$ − slope/channel protection rating$_{t0}$
	24. Air pollution	Emission amounts
	25. Water pollution	Emission amounts
	26. Noise pollution	Emission amounts

1998; Cook et al. 1994, 1990; de la Garza et al. 1998; Fitch et al. 2005; Flintsch 2004; Greitzer 1976; JLARC 2002; Misra and Das 2003; Rouse et al. 1997b; Simpson et al. 2006; TRB 1997, 2006; Venner 2005; Williams and Stensland 2006). Such list, along with the explanations and/or metrics for each of the input-output variables and uncontrollable factors is presented in Table 1.

It is important to note that while developing the list of input-output variables and uncontrollable factors shown in Table 1, every effort has been made to identify most of the variables that relate to the maintenance of bridges. When developing this list, specific attention has been given to identify the factors that (1) affect the deterioration of bridges (e.g., climate) and (2) affect the maintenance efforts (e.g., location of the bridge). Once this list was developed, it was presented to the decision makers in the maintenance division of VDOT for further input. The decision makers, after reviewing the list, commented that the list presented a good overall representation of input-output variables and uncontrollable factors that relate to the bridge maintenance process in Virginia. Nevertheless, the reader should be cautioned that when the framework presented in this paper is implemented in other states, it would be beneficial to have the list reevaluated to ensure that it provides a good representation and, if that is not the case, to add more variables or deduct the ones that are not applicable based on the feedback received from the maintenance decision makers within the transportation agency.

Deciding on the Size of the Decision-Making Unit (Component 2)

The input-output variables and uncontrollable factors pertaining to the maintenance of bridges were presented in the preceding section. Considering every input-output variables and uncontrollable factors (collectively called as "variables" hereafter) which have an impact on the bridge maintenance efficiency of the DMUs resulted in a list which is composed of a large number of variables. As presented earlier, one of the strengths of the DEA approach is its capability to measure the efficiency of processes with multiple variables. Nonetheless, running the DEA model using a very large number of variables would shift the compared DMUs toward the efficient frontier, resulting in a large number of DMUs to have high efficiency scores (labeled in the literature as the curse of dimensionality). This is a major limitation of the DEA approach. 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 discrimination. A DMU for which one particular ratio of an output to an input is the highest (of all DMUs for the same ratio) can allocate all of its weight to such ratio and become efficient. The total number of such ratios that is present in any DEA model can be as many as the product of the number of inputs and outputs included in such model. 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 very likely 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 $2mt$, where m is the number of inputs and t is the number of outputs (Boussofiane et al. 1991; Dyson et al. 2001). Such rule of thumb should be considered in deciding on the size of the DMUs that would be included in the models. Needless to say, such rule of thumb goes both ways; i.e., the number of variables (m and t) should also be small enough to help the DEA models to discriminate among the DMUs. In other words, the list of variables should be reinvestigated and refined [as will be discussed in the "Refining the Comprehensive List of Variables (Component 4)" section] to be able to increase the discriminating power of the DEA models without compromising the specification of the most important factors that are representative of the underlying production process. Nevertheless, every effort should be made to choose the size of the DMU such that the number of DMUs included in the models can be increased to the best extent possible.

As mentioned in the "Introduction," the writers have been involved in performing research to evaluate VDOT and its contractors for their level-of-service effectiveness. As a result of such effort, the writers have gathered a substantial amount of level-of-service data for 256 bridges that are located within approximately 430 directional mi (215 centerline mi) of interstate which is maintained by VDOT. In an effort to generate a large set of DMUs to compensate for the large set of variables presented in Table 1, initially it was decided to define the DMU as a 10-mi-long interstate section. This way, the number of DMUs could be maximized while assigning a meaningful size to such DMUs as far as DEA is concerned (i.e., the DMU is indeed a unit for which decisions are made). Such a definition would yield 43 DMUs, which is likely to be a sufficient number (as far as the discriminating power of DEA is concerned) once the comprehensive list of variables is refined, as discussed above. It is acknowledged that some of the 10-mi-long sections may not have any bridge and this would result in a decrease in the number of DMUs, i.e., 43 is the maximum number of DMUs that can be included in the model. However, defining a DMU as a 10-mi-long interstate section presented a major obstacle in the data gathering process. It was indicated by VDOT that the data for arguably the most important variable, the cost variable, cannot be gathered at a 10-mi-long interstate section level as VDOT's financial management system keeps track of the costs at the county level for each interstate. This restriction (i.e., county is the minimum size of a DMU at which the cost data are available) led to a modeling issue and dictated the selection of the DMU. Based on the data availability, the DMU to be used in the DEA model was changed from a 10-mi-long interstate section to a county. The counties of Virginia that encompass the portions of the interstate system under investigation (for which we have level-of-service data) were Albemarle, Alleghany, Augusta, Fauquier, Henrico, Roanoke, Rockbridge, and Spotsylvania. However, the cost data for the Roanoke County were, later on, identified to contain errors. Therefore, Roanoke County was removed from the analysis even though we had the level-of-service data for the bridges within such county. As a result, we were able to include 229 bridges that are located across seven counties (Albemarle, Alleghany, Augusta, Fauquier, Henrico, Rockbridge, and Spotsylvania) in the analysis.

Dealing with Uncontrollable Factors (Component 3)

Within the context of DEA, an uncontrollable factor is the factor that the decision maker has no control or influence over. Nonetheless, it affects the transformation process as it may affect the ability of a DMU adversely in generating more of its outputs using a given amount of inputs or similarly it may preclude the DMU from reducing its inputs beyond a certain amount to produce a given amount of outputs. Given their effects on the efficiency of the DMUs, all uncontrollable factors should be considered in the assessment of relative efficiencies among DMUs (Burley 2006; Golany and Roll 1993; Rouse et al. 1997a). However, traditional DEA formulations do not consider the effects of the uncontrollable factors on the performance of the DMUs (Dyson et al. 2001). This leads to the unfair comparison of DMUs in the presence of uncontrollable factors. Thus, to be able to perform fair comparison of units using DEA and to derive meaningful results that could be used by the decision makers to improve performance of such units, one needs to consider such factors in one way or another in the DEA models.

The phenomenon of uncontrollable factors gains utmost importance in the engineering applications of DEA, specifically in the case that is investigated within this research. Road maintenance is a process that is greatly affected by the uncontrollable factors. As a matter of fact, it is not only affected by the uncontrollable factors of the environment that it is performed within (such as climate, terrain, location, and subsurface conditions) but also by the uncontrollable factors representing the operational issues encountered by such process (such as design and construction adequacy, traffic and load, traffic accidents, aging, and area served). The aforementioned uncontrollable factors have a substantial effect on the road maintenance process and its efficiency. Given this, it is essential to consider such uncontrollable factors in the DEA models of the road maintenance process as they are very likely to explain the majority of the inefficiencies (of the DMUs) that would otherwise be observed in the DEA model runs in which they are disregarded.

A thorough review of literature identified the following approaches as being commonly used in the DEA studies to deal with

Table 2. Final List of Variables to Be Used in the DEA Models for Bridges

Variable type	Variable name	Variable explanation and/or metric
Input	Cost for maintaining the bridges	Dollars
	Regional effect variable	A grade (low, medium, or severe) based on the effect [using the results of Dadson's study (Dadson 2001; Dadson et al. 2002)]
	Total area served	Sum of the area (deck length × deck width) of all of the bridges within the DMU
Output	Change in overall bridge condition	Bridge rating_{t1} − bridge rating_{t0}

uncontrollable factors (Banker and Morey 1986a,b; Muniz et al. 2006; Ruggiero 1996, 1998; Simar and Wilson 2003; Xue and Harker 1999):

1. Uncontrollable factors treated as controllable variables in the DEA model;
2. Uncontrollable factors treated as uncontrollable variables in the DEA model;
3. Uncontrollable factors used to develop categories of DMUs to be included in the DEA models;
4. Continuous uncontrollable factors used to restrict the peer reference set;
5. Uncontrollable factors used to perform regression analysis over the obtained efficiency scores;
6. Parameters obtained by the regression analysis used to build an overall environmental harshness index; and
7. Uncontrollable factors used to perform bootstrapped regression analysis over the obtained efficiency scores.

Each of these approaches has a number of advantages and drawbacks as far as its applicability to certain scenarios is concerned. A detailed discussion of each of these approaches can be found in the research by Ozbek (2007). Of these approaches, the fourth one, which restricts the peer reference set for the DMU that is under investigation to the DMUs that face similar or harsher environments, is the one that is best suited to the case investigated in this research. Nonetheless, such approach requires a sufficiently large number of DMUs to be included in the models. Given the fact that the writers have only a few number of DMUs to be included in the models, such approach cannot be used. Rather, it has been decided to utilize the next best-suited approach. It is the second one in which the original DEA formulations are modified to include uncontrollable factors as uncontrollable input or output variables to estimate the extent to which inputs can be reduced (or outputs can be increased) by the decision maker while keeping the uncontrollable variables at their given level.

As can be grasped from the discussion presented above, the availability of data which determined the number of DMUs to be included in the model also dictated the approach that can be used to deal with the uncontrollable factors.

Refining the Comprehensive List of Variables (Component 4)

Given the discussion presented in the "Deciding on the Size of the Decision-Making Unit (Component 2)" section, once the initial comprehensive list of variables was developed, such list had to be reinvestigated and refined to be able to increase the discriminating power of the DEA models. Such refinement had to be made to the best extent possible to compensate for the few number of DMUs available to be included in the models. There are two main approaches that are commonly used in the DEA literature to refine the list of variables: (1) judgmental process and (2) quantitative analyses. Judgmental process involves methods such as assigning weights to variables based on judgment and the analytic hierarchy process (AHP) that requires the subjective input of the decision makers. Quantitative analyses, on the other hand, depend typically on statistical representations used to identify the relationships among different variables in an effort to remove a variable that is already represented by other variables in the data set or to aggregate multiple variables into one single variable that represents all of these variables (Ozbek 2007).

On the inputs side, the research by Dadson et al. (2002) was used to perform the necessary aggregation. Dadson et al. divide the state of Virginia into six regions by grouping together the areas that have similar terrain and climatic conditions such as rainfall, snowfall, humidity, temperature, and freeze-thaw cycles (Dadson 2001; Dadson et al. 2002). By using the environmental effects and operational effects such as the annual average daily traffic values and performing statistical analyses (analysis of variance), Dadson et al. assigned each region a grade (low, medium, or severe) based on its effect on the deterioration of bridges. Using the results of such study, the initial comprehensive list of uncontrollable factors, as shown in Table 1, could be reduced significantly to what is shown in Table 2 below as such study accounts for all of the uncontrollable factors listed in Table 1 but one (Variable 19—total area served) in assigning the grades to the regions of Virginia. It is important to note that de la Garza et al. utilized two alternative and very different approaches (AHP and regression analysis) for the refinement of the list of input variables, run the DEA models, and obtain very similar results (i.e., efficiency scores) to the ones that are obtained by running the model using the list of input variables refined by the method discussed above (de la Garza et al. 2009).

Another refinement can be made on the outputs side. The NBI data consist of the ratings for *deck* (labeled as 20 in Table 1), *superstructure* (21), *substructure* (22), and *slope/channel protection* (23) conditions. However, cost data with respect to the maintenance of slope/channel protection (23) are not made available to the writers by VDOT. Thus, such variable also needs to be removed from the analysis. The remaining three output variables (20, 21, and 22) can be combined into one variable, "change in overall bridge condition," by using a weighting scheme that is developed and implemented by the writers as agreed by the decision makers in the maintenance division of VDOT (de la Garza 2007). Such weighting scheme is developed using a National Cooperative Highway Research Program study (Stivers et al. 1997) which calls for the assignment of weights to different highway elements based on the importance of those elements as perceived by the transportation agency. The output variables *air pollution* (labeled as 24 in Table 1), *water pollution* (25), and *noise pollution* (26) can directly be removed from the list. They are different from the common concept of the output of a process as they are undesirable outputs (i.e., the less of them, the better). From an efficiency point of view, the inclusion of them in the DEA model is not critical but nonetheless given the availability of data, they should be included in the model. For our case, they will be disregarded since (1) no data are available for those undesirable outputs and (2) those variables are not deemed critical as far as their effect on overall efficiency of a DMU is concerned.

By performing the aggregations and removals discussed above, the final list of variables to be used in the DEA models becomes significantly shorter than the initially developed comprehensive list, as shown in Table 2.

Summary

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

This paper, being the first one in a series, provided the theoretical background on the DEA approach and introduced the framework developed to measure the efficiency of road maintenance operations while considering the uncontrollable factors affecting such efficiency. Being limited to presenting the early phases of such framework, this paper discussed the data and modeling issues associated with those phases, as illustrated in the case for VDOT. Nonetheless, as detailed within this paper, such issues were addressed to the best extent possible given the restrictions resulting from data and thus Component 1–Component 4 of the developed framework could be implemented in a real case.

Component 5–Component 9 of the framework, which is available in a companion paper (Ozbek et al. 2010), presents the core implementation stages of the framework. Such stages relate to performing the actual DEA model runs, obtaining the results, drawing conclusions from such results [such as identifying benchmarks (peers), targets, and the effects of the uncontrollable factors on the efficiency of the units], and influencing the decision-making process based on such conclusions.

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