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Measuring dynamic efficiency of highway maintenance operations ☆

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ABSTRACT

In this paper we discuss a dynamic efficiency measurement model for evaluating the performance of highway maintenance policies where the inter-temporal dependencies between consumption of inputs (i.e., maintenance budget) and realization of outputs (i.e., improvement in road condition) are explicitly captured. We build on a micro representation of pavement deterioration and renewal processes and study the impact of the allocation of scarce maintenance budgets over time. We provide a measure of efficiency that contrasts the optimized budget allocations to the actual ones. The developed model is then applied to an empirical dataset of pavement condition and maintenance expenditures over the years 2002 to 2008 corresponding to seventeen miles of interstate highway that lay in one of the counties in the state of Virginia, USA. The policies that were found through optimization showed that road authorities should give higher priorities to preventive maintenance than corrective maintenance. In essence, by applying preventive maintenance, the road authorities can effectively decrease the need for future corrective maintenance while spending less overall.

1. Introduction

1.1. Background and objectives

The objective of this paper is to provide a dynamic efficiency measurement model for evaluating the performance of highway maintenance policies where the inter-temporal dependencies between consumption of inputs (i.e., maintenance budget) and realization of outputs (i.e., improvement in road condition) are explicitly captured. The developed model is then applied to an empirical dataset of pavement condition and maintenance expenditures over the years 2002 to 2008 corresponding to seventeen miles of interstate highway that lay in one of the counties in the state of Virginia, USA. The motivation for conducting this study stems in part from the importance of improving effectiveness of highway maintenance policies in the context of rapidly deteriorating highway networks [1] and major budgetary restrictions.

However, a key prerequisite for the successful “improvement” of the performance of maintenance policies is the successful “measurement” of their performance. Several studies exist in the literature that focus on the measurement of the performance of highway maintenance operations in Ontario, Canada [2–4], New Zealand [5,6], and Virginia, USA [7–12]. All these studies focus on applying Data Envelopment Analysis (DEA) models for selected measures of outcomes (e.g., improvement in road condition) as outputs, and maintenance expenditures and environmental conditions as inputs. DEA models [13] use non-parametric methods as well as input/output data to construct a piecewise-linear function that acts as a benchmark for measuring the relative efficiency of a set of similar decision making units and have been widely used in various domains such as banking [14,15], agriculture [16,17], and healthcare [18], among others. Another common characteristic of the above mentioned studies [2–12] is that they assume that there is no time interdependence between the utilization of inputs (i.e., maintenance expenditures) and realization of outputs (i.e., improvement in road condition) in a highway network over consecutive periods. Instead, it is assumed that

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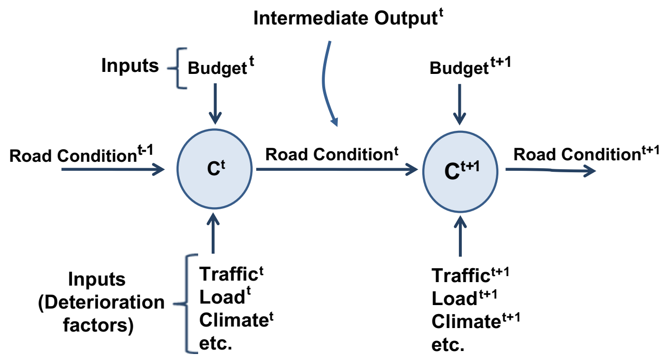

Fig. 1. Schematic view of the road condition evolution over time.

inputs in a specific period are fully used for producing outputs in the same period. However, in most real world applications, the effects of input consumption as well as the managerial/engineering decisions in one period will typically extend over several consecutive periods. This is the case for highway maintenance operations, when the utilization of the maintenance budget and treatments that are performed in a road section in a specific year directly affect the road condition and the required maintenance operations in subsequent years.

For a better understanding, Fig. 1 illustrates a schematic view of the road condition evolution over time. Assume that part of the highway network (represented by C) at period t is affected/deteriorated by a set of deterioration factors such as precipitation, traffic load, etc. Based on the condition of the road, appropriate maintenance operations are performed and the road evolves to a new condition at the end of period t. The new road condition is used as an input at the start of period $t+1$ when road section C goes under a similar transformation process. In other words, the maintenance treatments during period t affect the road condition at the end of period t which is the starting point for period $t+1$. Thus, the required maintenance operations during period $t+1$ (and consequently the road condition at the end of period $t+1$) depend on the maintenance operations/inputs that have been performed/used in a stream of previous periods.

In such a setting, any "static" efficiency measurement framework that ignores the inter-temporal effects of inputs and managerial decisions for future streams of outputs (i.e., future road conditions) is likely to be biased and/or unrealistic. The premise of this research is that successful evaluation and improvement of the performance of road maintenance practices requires a long-term perspective that takes into account the dynamics of road deterioration and maintenance.

As a result, the objective of this paper is to consider the shortcomings of previous studies by (i) realizing and acknowledging the presence of time interdependencies between inputs and outputs in the context of highway maintenance; and (ii) developing a dynamic efficiency measurement model of highway maintenance operations where we assume a nonlinear feedback system taking into account uncontrollable environmental factors (e.g., climate) and operational conditions (e.g., traffic load) along with controllable factors (e.g., budget allocation decisions).

1.2. The dynamics of highway maintenance operations

Fallah-Fini, Triantis, and Johnson [19] review the non-parametric dynamic efficiency literature and classify dynamic models according to five factors: (i) production delays (lagged outputs); (ii) inventories; (iii) capital or generally quasi-fixed factors; (iv) adjustment time and costs; and (v) incremental improvement and learning models. The models that capture adjustment cost/time typically assume that a production unit cannot instantly change the levels of quasi-fixed inputs (such as capital, labor, etc.) to their optimal values without incurring some costs of adjustment (typically in the form of forgone outputs). However investment in quasi-fixed inputs leads to expansion of future capacity and output. Thus, a trade-off occurs between current production and expansion for future production.

The dynamics of road deterioration and renewal processes (due to investment in maintenance operations) over time resembles the dynamics associated with investment in quasi-fixed factors in the presence of an "adjustment cost". The fact is that road authorities are responsible for planning and performing (either by using in-house crews or outsourcing) the required maintenance operations on the highway network in their administrative area in each year. The highway network under control of a road authority is divided into several road sections and the required maintenance operations are defined for each one of these sections. Due to limited budget, a decision to invest in maintenance operations for each road section takes the budget away from maintaining other road sections. This can potentially lead to worsening of the overall condition of the rest of the road sections. This situation can be treated as forgone output (cost of adjustment) associated with maintenance (investment) of road sections that have been maintained. However, since the maintained road sections will start with better conditions in the next period, we may experience an overall better condition of the whole road network in subsequent periods. Thus, a trade-off occurs between worsening the condition of some of the road sections at period t and improving the overall condition of the highway network in the future.

Different policies used for the allocation of the limited maintenance budget among road sections over time lead to different condition paths (adjustment paths) for the road sections and consequently, for the highway network under analysis. A question legitimately arises. What is the overall cost or value associated with following an optimum adjustment path (i.e., following an optimized budget allocation/investment policy) in comparison with the non-optimized ones? The dynamic performance measurement model provided in this paper assumes a long term perspective and measures the performance of road authorities with respect to their adjustment path (i.e., budget allocation policies for maintaining the highway network in their administrative area over time).

The remainder of this paper is organized as follows. Section 2 provides the methodology whereas Section 3 discusses the empirical results. Section 4 discusses insights and provides future research directions.

2. Methodology

We define a complete or partial highway network (composed of several road sections) as the system under analysis. The state of this system is defined by the "condition" of the highway network and is captured by an index called CCI (Critical Condition Index). The CCI represents the frequency and severity of different types of distress that exist in a road. Changes in the state of the system are partially endogenous, i.e. in response to the former state of the system. We divide the exogenous sources of change in the state of the system into factors that are controlled by organizational decision makers (e.g., budget allocation decisions) and those factors that are not controlled by the decision makers (e.g., environmental conditions, budget constraints). Let the vector $x(t)$ represent the state/condition of the system at time t. Then the dynamics of change in the state of the system follow a set of differential equations defined by the function $f(\cdot)$ as defined by Eq. (1).

$$\dot{x}(t) = f(x(t), I(t), u(t)) \tag{1}$$

where the dot over x denotes the derivative of x with respect to time, $I(t)$ represents the vector of exogenous inputs not controlled by