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# Data envelopment analysis for highway asset investment assessment

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## HIGHLIGHTS

- An implementable framework for cross-asset resources allocation was established.
- Different highway investment scenarios were benchmarked using existing tools or readily available data sets.
- Data envelopment analysis (DEA) approach and current widely used decision-making tools for highway investments were linked.

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## ABSTRACT

Highway agencies have been using many of the elements of asset management with the support of various decision-making tools. To determine the most effective investment strategy with scarce resources, the integration, and hence better utilization, of existing tools and practices across asset classes is generally lacking. This paper applies data envelopment analysis (DEA) to benchmark different highway investment scenarios using existing data or data readily available through existing models. Three asset types, pavements, bridges, and traffic signage, are investigated. Asset investment analysis results from the Highway Economic Requirements System State Version (HERS-ST) application, the PONTIS bridge management system software, and purpose-built traffic signage spreadsheet are obtained to capture the changes of performance measures under various budget scenarios and are further used as the inputs for the DEA process to benchmark investment scenarios for each individual asset. Subsequently, the performance measures and budget levels are assembled in the Asset Manager-NT software, whose results are input into DEA to benchmark cross-assets resource allocation scenarios. Planning for the management of highway network is addressed via case studies in a systematic manner that recognizes the tradeoffs among different funding periods and objectives such as preserving existing investments, safety, roughness and user costs. This study has established a preliminary implementable framework of highway asset management by linking DEA approach and current widely used decision-making tools for more efficient investments within and cross assets, and better understand of the tradeoffs, costs and consequences of various asset management decisions.

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## 1. Introduction

At its core, asset management is about using limited transportation dollars in the most cost-effective way possible (AASHTO, 2011; Adey, 2017; McNeil et al., 2008; Taggart et al., 2014). A fundamental challenge in managing transportation infrastructure assets is to determine how to allocate scarce resources among disparate asset categories (roads, bridges, safety, mobility, etc.) and types of needs (replacement, rehabilitation, routine maintenance, etc.) (Bai et al., 2011, 2015; Cambridge Systematics, Inc., 2006; Dehghanisanij et al., 2010; Fwa and Farhan, 2012; Li et al., 2012; Li and Sinha, 2004; Mrawira and Amador, 2009; Pagano et al., 2005; Wu et al., 2012).

Allocating resources between these areas is a complex problem requiring consideration of multiple objectives and constraints. To achieve the best results at both the individual asset system and the overall system levels, given a budget, five types of approaches are traditionally used for fund appropriation among competing highway asset components (Fwa and Farhan, 2012): (1) appropriation of funds based on historical allocations to the individual asset with minor adjustments to allow for special requirements (OECD, 2001); (2) formula-based appropriation, whose funds are allocated according to a predetermined formula based on engineering judgment or past experience consisting of selected parameters from the various assets (such as empirical regression models); (3) asset value-based appropriation, which implicitly assumes that the maintenance needs of each asset is proportional to its asset value (Jani, 2007; Sirirangsi et al., 2003); (4) maintenance needs-based appropriation, which allocates the available funds in proportion to the maintenance needs of each individual asset, but does not address optimality for the overall asset system (Flintsch and Bryant Jr., 2006); and (5) performance-based appropriation, which ties fund appropriation with the desired performance level of each asset component (Cowe et al., 2006; Gharaibeh et al., 1999, 2006). All approaches suffer limitations as they do not achieve optimality at both individual and overall system levels simultaneously.

To overcome the limitations of the conventional approaches, the use of optimization approaches for optimal cost allocation of highway assets has received increasing attention in the last few decades because of more stringent budgets, increasing demands, and stricter accountability in transportation investments and policy-setting decisions. Single-objective optimization identifies the best feasible solution in terms of an aggregate measure using priority weights, or an empirical index (Chan et al., 2003; Kuhn, 2010; Mrawira and Amador, 2009; Sadek et al., 2003; Small and Swisher, 2000; Zhang et al., 2002). Multi-objective optimization problems involve finding a vector of decision variables that satisfies constraints and optimizes various objective functions (Bai et al., 2011; Dehghanisanij et al., 2010; Li and Sinha, 2004; Mrawira and Amador, 2009). However, optimization techniques can be used to estimate the efficient frontier only if the functional forms for the relationships among various performance measures are known. In reality there are several challenges: (1) the priori information for making the tradeoffs is generally unknown or partially known, (2) the required data sets for comprehensive modeling are lacking and assumptions have to be made. In addition, many methods often rely on weighting benefits or outputs to combine different funding periods and multiple outputs (Cambridge Systematics, Inc., 2005; Li and Sinha, 2009; Wu and Flintsch, 2009). These weighting factors are generally decided by experts and prone to subjective preferences (Camp, 1995; Zhu, 2009). Further, the use of single measures ignores any interactions, substitutions or tradeoffs among various performance measures. As a result, the exact functional forms cannot be easily specified and implemented for state highway agencies to fully characterize and evaluate the efficiency of performance to benchmark the best practice.

On the other hand, highway agencies have been successfully using many of the elements of asset management, particularly pavement and bridge management and recently congestion, safety, and maintenance systems, to assist in establishing cost-effective strategies to sustain an acceptable condition of such facilities. Accordingly, dozens of decision-making tools have been developed in the past decades (Cambridge Systematics, Inc., 2005, 2009; Zhang et al., 2015). Linking and integrating these various activities currently used within highway agencies is necessary and of great importance to develop seamless, consistent and comprehensive management strategies. Specifically, filling the gaps in data and procedures, and exploring the integration of existing management systems and decision-making tools promises to be an effective strategy to support allocating budgets within an individual and among multiple assets.

To address the above-mentioned difficulties and achieve the goal to better utilize existing tools and practices, this paper adopts data envelopment analysis (DEA) to benchmark different highway asset investment scenarios. DEA is a linear programming methodology to measure the efficiency of multiple Decision-Making Units (DMUs) (Cooper et al., 2011; Li et al., 2011). Each DMU has a set of inputs and outputs, representing multiple performance measures of a business operation or process. In this study, the DMUs are investment scenarios. DEA process has several advantages, such as no need to explicitly specify a mathematical form for the production function, its capability of handling multiple inputs and outputs, etc., and has gained increasing application in numerous areas, such as business (Barnum et al., 2016; Charnes et al., 1985; McWilliams et al., 2014), supply chain (Cooper et al., 2006; Liang et al., 2006), and transportation (Barnum et al., 2007, 2008; Li et al., 2011; Ozbek et al., 2009, 2010a; 2010b; Wanke et al., 2016; Zhang et al., 2015).

To the extent possible, the application in this paper uses existing data or data readily available through existing models. The investment analysis results from the HERS-ST application, PONTIS system, and purpose-built traffic signage spreadsheet are obtained to capture the changes in performance measures under various budget scenarios and are used in the DEA process to benchmark the scenarios within each individual asset. Subsequently, the performance measures and budgets are assembled in Asset Manager-NT, whose results are used to benchmark cross-asset investments and resource allocation scenarios. The data sets in this study are from the state of Delaware.

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**Table 1 – Interstate and interstate-like highway assets under study.**

| Route | Route miles | Lane miles | AADT range | VMT (million) | # signs | Panel area (sf) | Exit area (sf) |
|---|---|---|---|---|---|---|---|
| I-95 | 23.3 | 162.8 | 35,332–173,449 | 813 | 82 | 10,285 | 558 |
| I-295 | 4.6 | 21.5 | 66,541–91,742 | 133 | 7 | 1093 | 0 |
| I-495 | 12.5 | 72.5 | 18,088–79,746 | 296 | 30 | 4466 | 253 |
| SR1 | 28.4 | 124.5 | 29,785–71,024 | 391 | 162 | 14,932 | 842 |

## 2. Data and tools

### 2.1. *Highway assets under study*

This study aims to apply the asset management framework to the interstate and interstate-like highways in Delaware that are significant not just for Delaware but for the Atlantic states and the nation, including I-95, I-495, I-295, and the tolled portion of State Route 1 (SR-1), which was constructed and maintained to standards similar to those for the interstate highways. In consultation with the project advisory committee, the scope of the work was defined in terms of the asset considered and the time frame. Three types of assets are selected for the project: pavement, bridge, and traffic signage. These assets were selected to illustrate the concepts and help to develop a plan for including other assets when data are available and consistent. The time frame for the analysis is selected to ensure consistency using a planning horizon of 20 years, making up four five-year funding periods.

Table 1 summarizes the characteristics of the roads considered in the case study. On these roads, there are 208 bridges with a total deck area of 412,217 square meters (4,437,071 square feet). The traffic signage spreadsheet database maintained at the Delaware Department of Transportation (DelDOT) includes the inventory of I-beam signs (281 with a total panel area of 3012.6 square meters (32,427.5 square feet)) and over-head signs (279 with 5179.2 square meters (55,748.9 square feet)), however, no retro-reflectivity reading was recorded for over-head signs and thus excluded.

### 2.2. *Decision-making tools*

Implementing asset management framework is facilitated by access to decision-making tools, which can be used to support tradeoff analysis and help decision makers to set targets for their highway systems. Various applications and decision-making tools have been developed in the state and federal levels. In this study, HERS-ST for pavement asset, PONTIS for bridge, and purpose-built spreadsheet for traffic signage are used to capture the changes in performance measures under various budget scenarios. The performance measures and budgets derived from these tools or systems are assembled in Asset Manager-NT to examine the implication of investment scenarios on their performance within and cross assets and alternative combinations explored.

- **HERS-ST** is a state version of FHWA's Highway Economic Requirements System (HERS) for highway investment analysis (Federal Highway Administration (FHWA), 2005). HERS-ST analysis provides the investment costs and the corresponding benefits by funding period for each alternative investment scenario, and assesses the economic efficiency based on incremental benefit cost analysis.
- **PONTIS** is a comprehensive bridge management system based on bridge inventory and inspection data (AASHTO, 2010). The system formulates network-wide preservation and improvement policies for use in evaluating the needs of each bridge in a network, and makes recommendations of projects for an agency's capital plan with maximum benefit from limited funds.
- **Asset Manager-NT** is a visualization tool that enables users to explore the performance implications of various resource allocation scenarios (Cambridge Systematics, Inc., 2005). The tool integrates analysis results from other decision-support tools (in this case HERS-ST and PONTIS) and provides a quick-response “what-if” analysis tool to explore alternative investment options.

## 3. Data envelopment analysis (DEA)

Data envelopment analysis (DEA) is used in the study to benchmark investment scenarios. DEA is a multi-factor productivity analysis model for measuring the relative efficiencies of a homogenous set of decision-making units (DMUs). The efficiency frontier defines the maximum combinations of outputs that can be produced for a given set of inputs. Assuming a set of $n$ scenarios as DMUs, each DMU$_j$ ($j = 1, \cdots, n$) uses $m$ inputs $x_{ij}$ ($i = 1, 2, \cdots, m$) to produce $s$ outputs $y_{rj}$ ($r = 1, 2, \cdots, s$). The input-oriented envelopment models with variable returns of scale (VRS), one of the most widely used model to determine frontiers, can be formulated in Eq. (1) to minimize the inputs while keep the outputs at their current levels (Camp, 1995; Cooper et al., 2011; Zhu, 2009).

$$\min\theta - \epsilon\left(\sum_{i=1}^{m} s_i^- + \sum_{r=1}^{s} s_r^+\right)$$

Subject to

$$\begin{cases} \sum_{j=1}^{n} \lambda_j x_{ij} + s_i^- = \theta x_{ip} & i = 1, 2, \cdots, m \\ \sum_{j=1}^{n} \lambda_j y_{rj} - s_r^+ = y_{rp} & r = 1, 2, \cdots, s \\ \sum_{j=1}^{n} \lambda_j = 1 & \\ \lambda_j \geq 0 & j = 1, 2, \cdots, n \end{cases} \tag{1}$$

The above problem is run $n$ times in identifying the relative efficiency scores of all DMUs. Each DMU selects input and output weights that maximize its efficiency score. In Eq. (1), DMU$_p$ is the target DMU (one of the $n$ DMUs under

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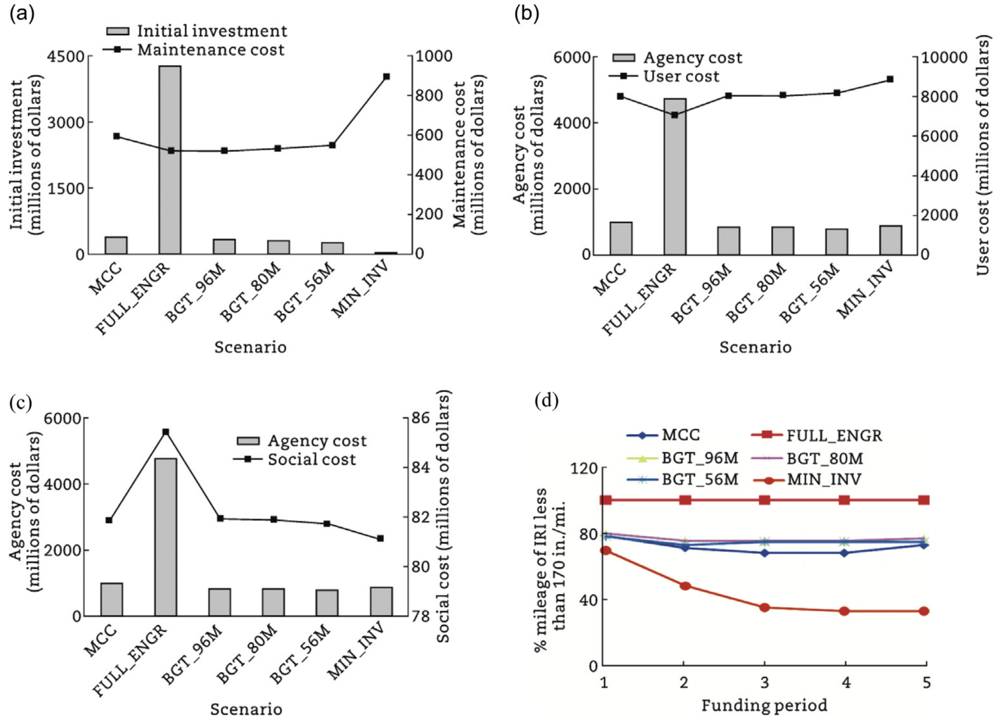

**Fig. 1 – HERS-ST pavement analysis results at various investment levels. (a) Agency cost. (b) User cost. (c) Social cost. (d) % mileage of IRI less than 170 in./mi.**

evaluation). $\theta$ represents the efficiency score of $DMU_p$. $x_{ij}$ and $y_{rj}$ are the $i$th input and $r$th output for $DMU_i$. $\lambda_j$ is the unknown weight to be determined. $s_i^-$ and $s_r^+$ are slacks of input and output. In general, if $\theta = 1$, the current input levels cannot be reduced, indicating that $DMU_p$ is on the frontier. Otherwise, if $\theta < 1$, $DMU_p$ is dominated by the frontier and is inefficient, or the DMU under evaluation can reduce its inputs by the proportion of $\theta$. $\epsilon > 0$ is a small non-Archimedean quantity.

It should be noted that in the conventional DEA models, such as the VRS envelopment models, it is desired that outputs should be increased (defined as desirable outputs) and the inputs should be decreased (defined as desirable inputs) to improve the performance or to reach the best-practice frontier in the DEA process. For undesirable inputs and/or outputs, several approaches have been developed. A simple method is to apply transformations, such as multiply undesirable output by "−1" and then find a proper constant to let all negative undesirable outputs be positive, which is used in this paper.

## 4. Investment scenarios and benchmarking of individual asset

### 4.1. *Pavement*

#### 4.1.1. *HERS-ST results*

Pavement data was obtained from DelDOT's Pavement Management System (PMS) and the Highway Performance Monitoring System (HPMS). HPMS data serves as an input to HERS-ST, and four types of investment scenarios are generated for modeling in HERS-ST.

- Minimum Investment ("Do-Nothing") (coded as "MIN_INV"): the highway section being considered remains unimproved for the duration of the analysis period and minimum investment is involved.
- Constrained by Funds: the base budget level is estimated from DelDOT's current practice, to be approximately $80 million for a 4-year funding period. This budget is then increased by 20% ($96 million) and decreased by 30% ($56 million) to generate comparative scenarios. The available budgets for each funding period are kept the same for all the periods. These scenarios are denoted as "BGT_96M", "BGT_80M", and "BGT_56M".
- Maintain Current Conditions (denoted as "MCC"): the level of system performance at the beginning of the run (derived from the HPMS data) is based on the current highway-user costs, and the least costly mix of improvements is selected to maintain that level of performance.
- Full Engineering (denoted as "FULL_ENGR"): without funding constraints, this scenario calculates the minimum funding required for each funding period in order to maintain the pavement condition rates "fair" and above.

HERS-ST generates four broad classes of costs by funding period: (1) initial capital improvement costs (in 1000$), (2) annual maintenance costs (in $/mile), (3) user costs (in dollars per 1000 vehicle mile travelled (VMT)), (4) external costs (in $/1000VMT) due to vehicular emissions of air pollutants and accident events. Maintenance costs and initial capital costs are summed to represent agency costs. In addition, the percent mileage of highway in poor and fair condition in terms of international roughness index (IRI) is obtained HERS-ST to represent highway performance.

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**Table 2 – Benchmarking of HERS-ST pavement investment scenarios.**

| DMU # | DMU name | Efficiency score | Benchmark | | | |
|---|---|---|---|---|---|---|
| | | | $\lambda_1$ | By | $\lambda_2$ | By |
| 1 | BGT_96M | 1.00 | 1.000 | BGT_96M | – | – |
| 2 | BGT_80M | 0.98 | 0.992 | BGT_96M | 0.008 | FULL_ENGR |
| 3 | BGT_56M | 0.89 | 0.980 | BGT_96M | 0.020 | FULL_ENGR |
| 4 | MCC | 0.92 | 0.914 | BGT_96M | 0.086 | FULL_ENGR |
| 5 | MIN_INV | 0.52 | 0.814 | BGT_96M | 0.186 | FULL_ENGR |
| 6 | FULL_ENGR | 1.00 | 1.000 | FULL_ENGR | – | – |

The cost components are summed up into aggregated values in constant dollars over the entire analysis period based on the values at each funding period. A 4% discount rate (*d*) is used in accessing the time value of money for all the cost related parameters, and all calculations are converted to the present worth values. Due to the differences in the units used, the calculations of undiscounted dollars vary. The initial capital requirements are provided in HERS-ST model in dollars. The maintenance cost equals to the maintenance costs per mile multiplied by the mileage of the network, while for user cost and emission cost, the corresponding costs from the HERS-ST model need to be multiplied by VMT during the funding period. The performance measures (% IRI less than 170 in./mi.) at the end of each funding periods are used as the outputs since an average or aggregate value doesn't have any practical meaning for this case. Fig. 1 demonstrates the aggregate net present cost values for the whole 20-year analysis period. The initial capital investment costs versus the maintenance costs, agency costs versus user costs, social costs, and highway IRI are plotted. A much higher initial investment in the “Full Engineering” scenario results in lower maintenance costs, lower user costs, better highway performance and higher social costs, while in the “Minimum Investment” scenario the opposite trends are observed.

### 4.1.2. *DEA benchmarking results*

The results for various scenarios from HERS-ST are used as inputs and outputs for the following DEA benchmarking. The inputs to the DEA analysis are the net present values of agency costs, including the initial capital requirements for each funding period and the corresponding maintenance costs. The outputs are the benefits of the highway system renewal, including performance improvement in terms of % mileage of highways with IRI less than 170 in./mi., net present values of user costs and social costs.

As above-mentioned, the inputs and outputs shall be desirable in order to apply the VRS envelopment model as illustrated in Eq. (1). However, since the inputs of this process are agency cost, the summation of initial capital investment (the cost component in HERS-ST) and the corresponding maintenance cost (the benefit or output of HERS-ST), it is not straightforward to judge which input/output is desirable. For example, by comparing the “MCC” and “BGT_56M” scenarios, the “BGT_56M” scenario has a relative lower capital investment but a higher maintenance cost than those in the “MCC” scenario. It is therefore challenging to determine which scenario has a better smoothness performance in terms of IRI. To identify whether the input/output is desirable, a correlation matrix is generated and the correlation coefficient is used to estimate the relationships and interactions among the input and output variables. If the correlation coefficient is negative, it is treated as undesirable. The correlation analysis shows the user cost has a negative correlation coefficient with the input, which indicates that it is an undesirable output and is consistent with what we expected since generally more agency investments (increased inputs) result in reductions in user costs. To make the output desirable, the original output is adjusted by multiplying this undesirable output by “−1” and then adding a proper constant to let all negative undesirable outputs be positive. All the other outputs, highway performance in terms of roughness and emission costs have positive correlations and are treated as desirable outputs.

Solving the linear programming DEA problem presented, the efficiency scores for the six analysis scenarios are shown in Table 2. The results demonstrate that the “BGT_96M” scenario, a 20% increase from the assumed current investment, has the highest efficiency score of 1.00 and is the benchmark of “BGT_80M”, “BGT_56M”, “MCC”, and “MIN_INV” scenarios. The efficiency score for the current budget level scenario (“BGT_80M”) is 98%, which indicates that if the outputs for that scenario are kept at current levels, the input (or the agency cost) can be reduced by 2% (which is 160, 000 dollars) if it is as efficient as its benchmark.

Even though the “Minimum Investment” scenario requires almost no initial investment, it generates much higher maintenance and worse highway performance, as a result, its efficiency score is only 52%. This supports the idea that under investment is not the most efficient way to manage our highway assets. On the other hand, the “Maintain Current Condition” scenario requires a slightly higher agency investment, however, its efficiency score is 92% of the benchmark investment alternative. From this perspective, it is shown that more investment doesn't guarantee a better overall outcome (in terms of efficiency). There is an optimal investment alternative to achieve the best overall system efficiency.

It is noted that the “Full Engineering” scenario is on the frontier with an efficiency score of 1.00. This scenario is significantly different from the other five scenarios, but still represents another point on the efficiency frontier. This assumption can be supported by the fact that it is benchmarked by itself and the other inefficient DMUs are minor benchmarked by the “FULL_ENGR” DMU, as shown in Table 2. Efficient DMUs consider themselves as their own “benchmark” while inefficient DMUs are benchmarked by multiple efficient DMUs. For example, the benchmarks for

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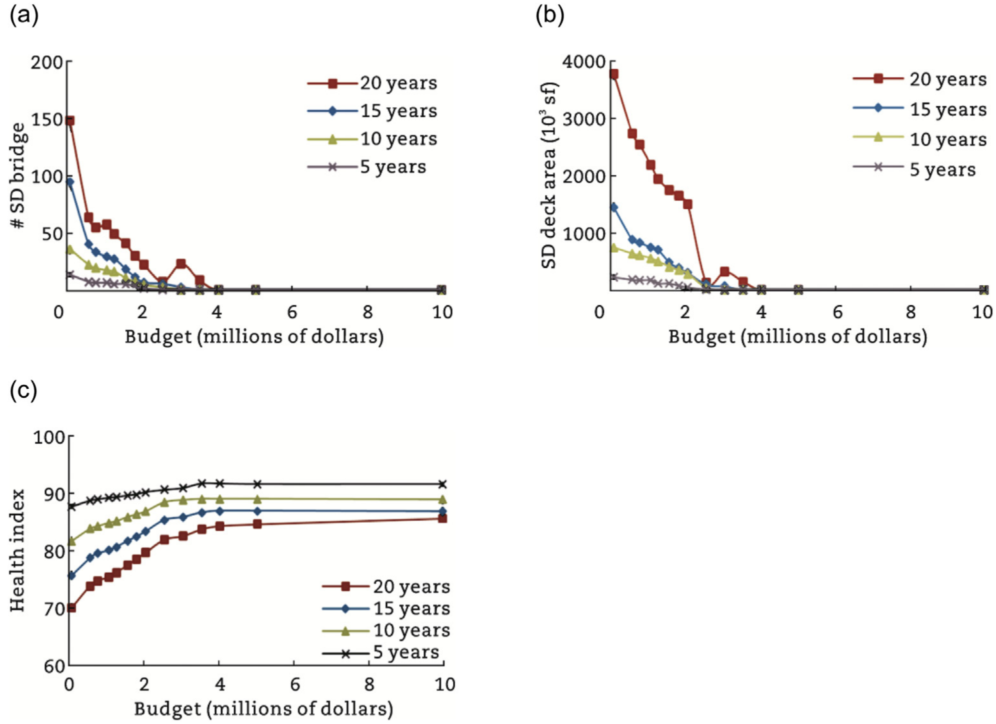

**Fig. 2 – PONTIS bridge analysis results at various investment levels. (a) #SD bridge. (b) SD deck area. (c) Health index.**

DMU #2 are DMUs #1 and #6. This means, to become efficient, DMU #2 must use a combination from both DMU #1 and DMU #6 (a virtual DMU) to be efficient. The benchmarking weights for the DMU #1 and DMU #6 combination are calculated and reported next to each benchmark DMU in order to achieve frontier efficiency. In this case, DMU #2 will attempt to become more like DMU #1 other than DMU #6 as observed from the respective $\lambda$ weights ($\lambda_1 = 0.992$ vs. $\lambda_2 = 0.008$).

## 4.2. *Bridge*

### 4.2.1. *PONTIS results*

Bridge data from the National Bridge Inventory (NBI) serves as input to PONTIS that in turn is used to generate investment scenarios. The most current NBI data sets were imported into PONTIS management system. Ten budget levels, from 0 to 10 million dollars per year were simulated. These resources were used by PONTIS to recommended maintenance work bridge-by-bridge. The network results, in terms of structurally deficient (SD) bridges by the number of bridges and by deck areas (in $10^3$ square feet), and the bridge health index currently used in DelDOT, are presented in Fig. 2.

It is noted that PONTIS dollars do not reflect the total cost to maintain the bridges. PONTIS only uses the direct cost to perform maintenance actions and does not include indirect costs, such as traffic control, erosion control, and design costs. Based on a DelDOT internal study, the total cost is determined to be about 3.1 times the direct cost based on results from a group of rehabilitation projects conducted in the State of Delaware (McNeil and Li, 2012). For example, if DelDOT is spending roughly \$4 million per year on this group of bridges based on the results from PONTIS, this \$4 million budget reflects a total cost of \$12.4 million.

### 4.2.2. *DEA benchmarking results*

DelDOT bridge engineering provided the results from PONTIS for ten scenarios representing budget levels from 0 to 10 million dollars. Using these scenarios, the input to the DEA analysis is the annual average budget for each scenario, while the outputs are the three performance measures discussed before. Even though these measures are simulated and recorded for each of the four funding periods, only the measures at the end of the 20-year analysis period are used as the DEA outputs. The reasons are: (1) currently there are no structurally deficient bridges, and the health index is over 92%, which indicates that the bridges are in excellent condition in terms of these measures; and (2) an analysis period of 20 years is relatively short comparing to the design lives of bridges. As a result, the deterioration in the coming 20 years turns out to be insignificant, and even less significant if only one funding period (5 years) is studied.

The desirability of the inputs and outputs are checked. The higher the percentage of structurally deficient bridges, the worse the performance of the bridges is. This correlation indicates that this measure is undesirable and needs to be preprocessed using the same method as that for pavement.

The efficiency scores of the bridge investment DMUs are shown in Table 3. It is noted that the scenario that spends the least achieves the best efficiency. Again, these results can be explained similarly to those when we choose the output performance measures. As a result, the costs needed for improvement outweigh the benefits of such improvement, concluding that no investment is the most efficient approach in the short term. This observation also reveals the challenges in selecting appropriate performance measures. The two performance measures that we adopted are not very sensitive to the amount of investment for

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**Table 3 – Benchmarking of PONTIS bridge investment scenarios.**

| DMU # | Annual budget (million) | % Non-SD by deck area | Health index | Efficiency score | Benchmark | |
|---|---|---|---|---|---|---|
| | | | | | $\lambda_1$ | By |
| 1 | 0.5 | 68.9 | 74.0 | 1.00 | 1.00 | DMU1 |
| 2 | 1.0 | 71.9 | 75.5 | 0.52 | 1.04 | DMU1 |
| 3 | 2.0 | 88.9 | 79.8 | 0.32 | 1.29 | DMU1 |
| 4 | 3.0 | 88.9 | 82.7 | 0.22 | 1.29 | DMU1 |
| 5 | 5.0 | 100.0 | 84.8 | 0.15 | 1.45 | DMU1 |
| 6 | 10.0 | 100.0 | 85.8 | 0.07 | 1.45 | DMU1 |

bridge infrastructure. It also raises awareness that using incremental benefit cost analysis (which is used in the PONTIS system) may limit the capture of the “true” benefits resulting from the investment.

## 4.3. *Traffic signage*

### 4.3.1. *Investment analysis*

DelDOT maintains a multiple year signage spreadsheet database which includes the installation date of the sign, its sheeting type, sign panel area, facing direction, and measures of retroreflectivity by color for multiple years for large ground-mounted I-beam signs. However, no software is available to manage the signs and a careful analysis of the data revealed inconsistencies in the data. As a result, no acceptable retroreflectivity deterioration model could be developed (McNeil and Li, 2012). In order to generate investment scenarios and their performance development, the following assumptions are made for large I-beam signs based on the consultation with DelDOT engineers based on previous experience.

- Expected sign life is 15 years.
- Average maintenance cost per sign per year is $30,000.
- Sign replacement cost is $16 per square foot, with total costs of $30 per square foot including the new sign panel, maintenance of traffic (MOT), and labor for removal of the old panel and installation of the new panel.

Based on these assumptions, six scenarios are generated. Spreadsheet based analyses were conducted and the performance development for the six investment scenarios (0, 5%, 10%, 20%, 30% and 40% of replacement per funding period denoted as S_1, S_2, S_3, S_4, S_5, and S_6). Two performance measures are adopted in this study to capture the performance for signage assets: % signs within their useful life by panel area and by the number of signs. The partial performance results are presented in Fig. 3.

It is observed that most of the signs are within their expected lives during the first and the second funding periods due to the facts that most of the signs were newly replaced. However, during the third and the fourth funding periods, the performance in terms of the measures used in the project depends on the budget level. The less the spending, the more signs are beyond their useful lives. The results also reveal that when the replacement per funding period exceeds 30%, almost all the signs are within the expected lives.

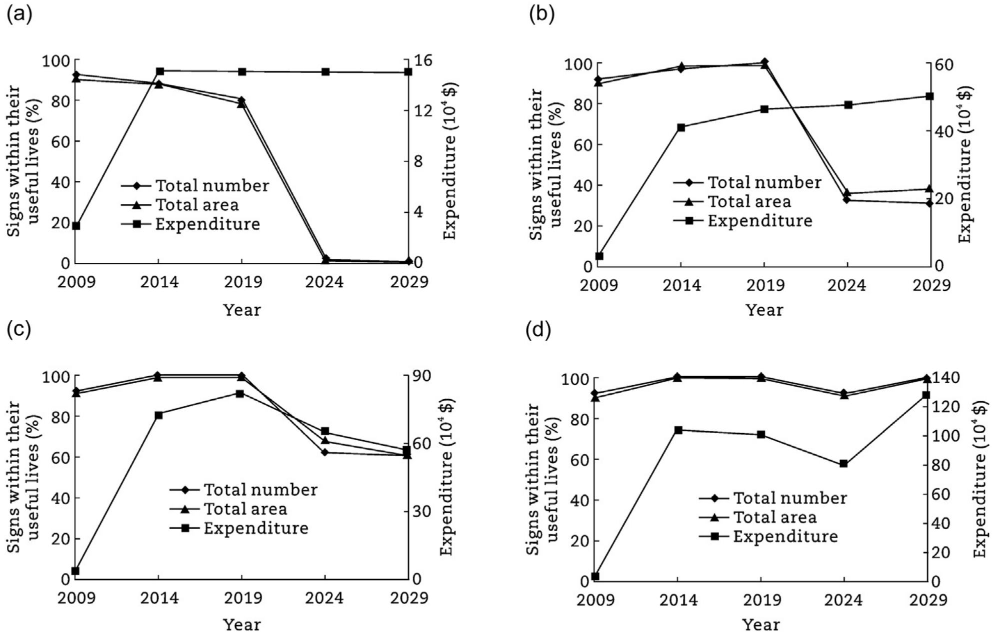

**Fig. 3 – Signage analysis results at various investment levels. (a) Do-Nothing. (b) 10% replacement per funding period. (c) 20% replacement per funding period. (d) 30% replacement per funding period.**

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### 4.3.2. *DEA benchmarking results*

The previous developed six investment scenarios are analyzed as six DMUs for the DEA benchmarking process. The annual budget requirements for each scenario are used as the inputs, while the two performance measures as the outputs. Since the majority of signs on the highways under study have been replaced in the most recent five years, only the performance measurement values at the end of the analysis period are used as the outputs for the DMUs. In order to improve the efficiency of the signage investment, we would like to achieve higher percentage of signs within their useful life with less investment. In other words, the inputs and outputs of these DMUs are desirable and no data preprocessing or transformation is needed.

The efficiency analysis results are shown in Table 4. The results show that DMU #5 (30% replacement per funding period) receives an efficiency score of 1.0 and is considered to be efficient, while the rest of the investment scenarios are benchmarked by DMU #5 with efficiency scores of less than 1.0 but greater than 0, and thus they are identified as inefficient.

These DMUs can improve their efficiency, or reduce their inefficiencies proportionally, by reducing their inputs. For example, investment DMU #1 can improve its efficiency by reducing its input (investment dollars) up to 9.7% (which is 100% minus the efficiency score of 90.3%).

If the scenario is inefficient, which inputs/outputs are needed to be reduced by calculated proportions? These reductions are called slacks. Table 4 shows the DEA run results for the output slacks when the input keeps at the current level since input-oriented model is applied. It is observed that the efficient DMU #5 doesn't have any slacks. Slacks exist only for those DMUs identified as inefficient. However, slacks represent only the leftover proportions of inefficiencies. After proportional reductions in inputs or outputs, if a DMU cannot reach the efficiency frontier (to its efficiency target), slacks are needed to push the DMU to the frontier (target). For example, DMU #2 cannot reduce any input, but must augment the output in terms of % sign within expected life (by number of signs) by 1.9%. It is noted that DMUs #1 and #6 have no slacks in the input and output, which indicate that these DMUs can reach efficiency frontiers after proportional reduction in inputs or increase in outputs.

Table 4 also prescribes the target input and output levels for these scenarios. The targets are the results of respective slack values added to outputs. To calculate the target values for inputs, the input value is multiplied with an optimal efficiency score, and then the slack amount subtracted. As we can observe, the target values for efficient DMUs are equivalent to their original input and output values. For insufficient DMUs, in the VRS input-oriented DEA model, the targets for input variables will comprise proportional reduction in the input variables, by the efficiency score of the DMU minus the slack value. For example, the target input for DMU #3 can be calculated as 93,289 (original input) × 0.840 (efficiency score) - 0.00 × (input slack), which equals to 78,363. Similarly, the output targets can be calculated by adding the original output value and the slack.

## 5. Cross-asset investment benchmarking

### 5.1. *Data inputs and outputs*

The inputs and outputs for the cross-asset DEA analyses are obtained from the Asset Manager-NT software, who is capable of providing a quick-response “what-if” analysis tool for testing different investment options. The dashboard view lets decision makers adjust an overall system's annual budget interactively as it dynamically indicates the effect of the budget on different performance measures, but also provides the functionality of customizing the resources allocation among the asset type in percentage (Fig. 4). By using the dashboard view, the performance measure values at various resource allocation scenarios and various budget levels can be obtained and used as the inputs and outputs for further cross-asset DEA benchmarking.

Based on the real expenditure data in DelDOT and the engineering judgments of DelDOT engineers, it is estimated that (1) approximately $4.0 million (direct costs from PONTIS) has been spent on the bridges on the highways under study; (2) the total cost is about 3.1 times of direct cost; (3) the current resources allocation between bridges and pavements is around 25% vs. 75%; and (4) compared to expenditures on bridges and pavements, the spending on traffic signage is trivial. Accordingly, we can assume that the current practice annual budget for pavement and bridges are roughly 50 million dollars in terms of total costs, which are calculated as ($4.0 million × 3.1)/25% = $49.6 million. It should be noted that

**Table 4 – Benchmarking of traffic signage investment scenarios.**

| Criteria | | Measure | DMU1 | DMU2 | DMU3 | DMU4 | DMU5 | DMU6 |
|---|---|---|---|---|---|---|---|---|
| DEA analysis | Input | Annual budget ($) | 30,000 | 61,340 | 93,289 | 138,884 | 207,206 | 271,149 |
| | Output | % within expected life (panel area) | 0.00 | 17.08 | 37.81 | 60.26 | 100.00 | 100.00 |
| | | % within expected life (# signs) | 0.00 | 15.18 | 30.54 | 60.54 | 100.00 | 100.00 |
| | Efficiency score | | 0.07 | 0.58 | 0.84 | 0.90 | 1.00 | 0.76 |
| | Benchmark | $\lambda_1$ | 0.01 | 0.17 | 0.38 | 0.61 | 1.00 | 1.00 |
| | | By | DMU5 | DMU5 | DMU5 | DMU5 | DMU5 | DMU5 |
| Slack | Input | Annual budget ($) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | Output | % within expected life (panel area) | 0.00 | 0.00 | 0.00 | 0.28 | 0.00 | 0.00 |
| | | % within expected life (# signs) | 0.00 | 1.90 | 7.27 | 0.00 | 0.00 | 0.00 |
| Efficient target | Input | Annual budget ($) | 2100 | 35,577 | 78,363 | 124,996 | 207,206 | 206,073 |
| | Output | % within expected life (panel area) | 1.00 | 17.08 | 37.81 | 60.54 | 100.00 | 100.00 |
| | | % within expected life (# signs) | 1.00 | 17.08 | 37.81 | 60.54 | 100.00 | 100.00 |

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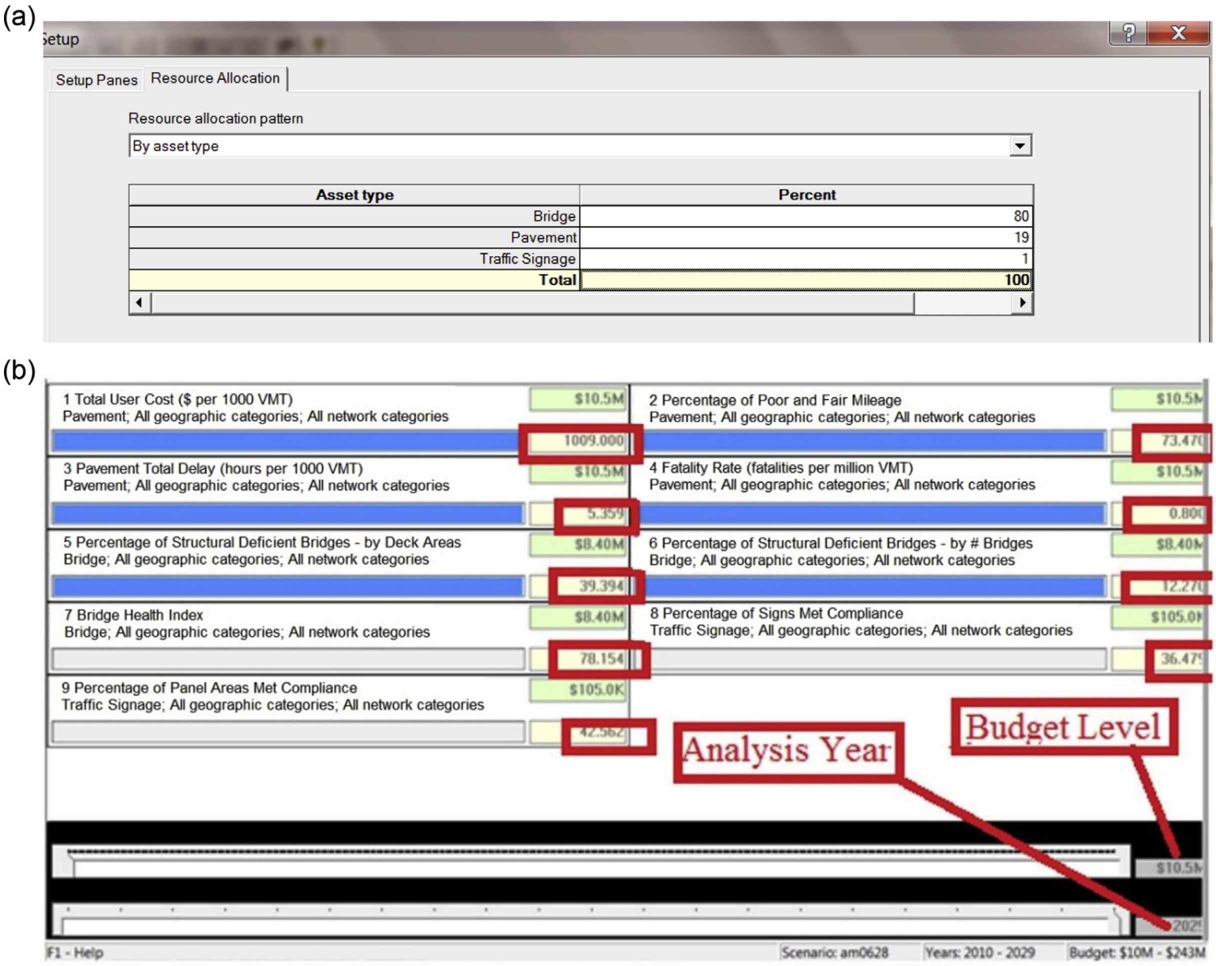

Resource allocation pattern: By asset type

| Asset type | Percent |
|---|---|
| Bridge | 80 |
| Pavement | 19 |
| Traffic Signage | 1 |
| **Total** | **100** |

1 Total User Cost ($ per 1000 VMT)
Pavement; All geographic categories; All network categories
$10.5M
1009.000

2 Percentage of Poor and Fair Mileage
Pavement; All geographic categories; All network categories
$10.5M
73.47

3 Pavement Total Delay (hours per 1000 VMT)
Pavement; All geographic categories; All network categories
$10.5M
5.359

4 Fatality Rate (fatalities per million VMT)
Pavement; All geographic categories; All network categories
$10.5M
0.80

5 Percentage of Structural Deficient Bridges - by Deck Areas
Bridge; All geographic categories; All network categories
$8.40M
39.394

6 Percentage of Structural Deficient Bridges - by # Bridges
Bridge; All geographic categories; All network categories
$8.40M
12.27

7 Bridge Health Index
Bridge; All geographic categories; All network categories
$8.40M
78.154

8 Percentage of Signs Met Compliance
Traffic Signage; All geographic categories; All network categories
$105.0
36.47

9 Percentage of Panel Areas Met Compliance
Traffic Signage; All geographic categories; All network categories
$105.0K
42.562

$10.5M
202

Scenario: am0628 Years: 2010 - 2029 Budget: $10M - $243M

**Fig. 4 – Asset Manager-NT dashboard view for cross-asset analysis. (a) Resources allocation. (b) Performance at various budget level and analysis year.**

this budget estimate is different from that from HERS-ST to maintain current condition for pavement only. This estimate is in total costs, while the HERS-ST requirement is in initial capital costs.

The previous section showed that when an annual budget of $200,000 dollars is spent for sign maintenance and replacement, the sign performance measures reach to their maximum values at 100%, but this spending accounts for only 0.4% of the estimated annual overall system budget of $50 million. However, when customizing the cross-assets resources allocation (in percentage) in the dashboard view of the Asset Manager-NT software, no decimal is allowed in the input. As a result, the smallest resource allocation for signage is 1%, which is $500,000 annually - 2.5 times of the spending that results in 100% of signs within their useful lives. Therefore, traffic signage assets are eliminated from the cross-assets analyses, and only bridges and pavements are considered.

### 5.2. *Various resource allocation scenarios*

The first analysis aims to examine the efficiency of various resource allocation scenarios at the current budget level of $50 million annually. Seven resource allocation scenarios are explored as shown in Table 5. The projected values of the performance measures for pavement and bridges are obtained from the Asset Manager-NT software. The system annual budget serves as the input of the DEA analysis, while the percentage in poor and fair conditions and total delay for pavement asset, the percentage of SD bridges by deck area and health index for bridge asset are utilized as outputs. The other two measures - total user cost and fatality rate are removed from the analysis because these measures demonstrate only minor variations among the allocation scenarios. The "% SD bridges by number of bridges" measure is removed as well due to its high correlations with the "% SD bridges by deck area" measure. Obviously, three outputs - the percentage in poor and fair conditions, total delay, and percentage of SD bridges by deck area are undesirable measures since the decreases of these measures result in better system performance. After they are adjusted to be desirable, the DEA analysis is performed and the efficiency scores of the allocation scenarios are presented in Table 5.

### 5.3. *Various budget level scenarios*

The objective of this second analysis is to explore the efficiency at various budget levels. The current resources

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**Table 5 – Benchmarking of cross-asset at various resource allocations.**

| Criteria | | | DMU1 | DMU2 | DMU3 | DMU4 | DMU5 | DMU6 | DMU7 |
|---|---|---|---|---|---|---|---|---|---|
| Input/output | Total budget ($10^6$ $) | | 50 | 50 | 50 | 50 | 50 | 50 | 50 |
| | Resource allocation (%) | Pavement | 100 | 90 | 80 | 75 | 70 | 60 | 50 |
| | | Bridge | 0 | 10 | 20 | 25 | 30 | 40 | 50 |
| | Pavement performance | % in poor & fair | 2.06 | 4.02 | 6.09 | 7.12 | 8.16 | 17.32 | 31.67 |
| | | Total delay | 1.42 | 1.69 | 2.01 | 2.17 | 2.33 | 2.84 | 3.49 |
| | Bridge performance | % SD bridges (deck area) | 100.00 | 69.32 | 23.38 | 0.00 | 0.00 | 0.00 | 0.00 |
| | | Health index | 64.40 | 74.10 | 76.68 | 81.92 | 82.29 | 83.04 | 83.78 |
| | Note | | Pavement only | In-between | In-between | Current practice | In-between | In-between | Even allocated |
| Result | Efficiency score | | 0.98 | 1.00 | 1.00 | 1.00 | 1.00 | 0.99 | 0.98 |
| | Benchmark | $\lambda_1$ | 1.03 | 1.00 | 1.00 | 1.00 | 1.00 | 1.01 | 1.02 |
| | | By | DMU2 | DMU2 | DMU3 | DMU4 | DMU5 | DMU5 | DMU5 |

**Table 6 – Benchmarking of cross-asset at various budget levels.**

| Criteria | | | DMU1 | DMU2 | DMU3 | DMU4 | DMU5 |
|---|---|---|---|---|---|---|---|
| Input/output | Total budget ($10^6$ $) | | 35 | 45 | 50 | 55 | 65 |
| | Resource allocation (%) | Pavement | 75 | 75 | 75 | 75 | 75 |
| | | Bridge | 25 | 25 | 25 | 25 | 25 |
| | Pavement performance | % in poor & fair | 28.17 | 8.70 | 7.12 | 5.61 | 2.53 |
| | | Total delay | 3.33 | 2.42 | 2.17 | 1.94 | 1.45 |
| | Bridge performance | % SD bridges (deck area) | 35.80 | 11.27 | 0.00 | 0.00 | 0.00 |
| | | Health index | 78.50 | 80.83 | 81.92 | 82.10 | 82.47 |
| | Note | | 30% decrease | 10% decrease | Current practice | 10% increase | 30% increase |
| Result | Efficiency score | | 1.00 | 1.00 | 1.00 | 0.91 | 0.78 |
| | Benchmark | $\lambda_1$ | 1.00 | 1.00 | 1.00 | 0.37 | 0.00 |
| | | By | DMU1 | DMU2 | DMU3 | DMU2 | DMU1 |
| | | $\lambda_2$ | – | – | – | 0.67 | 1.12 |
| | | By | – | – | – | DMU3 | DMU2 |

allocation practices between bridge and pavement (25% vs. 75%) is kept but five budget levels at the annual total budget of $50 million (current practice), $35 million (30% decrease), $45 million (10% decrease), $55 million (10% increase), and $65 million (30% increase) are explored (Table 6). The performance data are obtained from the Asset Manager-NT software. The efficiency scores for the various budget level scenarios with the adjusted undesirable outputs are illustrated in Table 6.

Comparing to the scenario of estimated $50 million in total costs, it shows that more aggressive investment scenarios are not as efficient as the decreased investment scenarios. This is mainly due to the situation that the current pavements and bridges are performing well in terms of the performance measures used. Another reason may be that the estimated current investment level ($50 million of total costs) is higher than the real practice investment. While DelDOT cannot directly determine how much is spent on managing the interstate-like assets, estimates of an annual budget of direct costs, and an empirical cost expansion factor have been made. The other assumption of this estimate is the resources allocation ratio between pavement and bridge (75% vs. 25%), which is a reasonable estimate but may not truly reflect the real spending either. If we would like to maintain the health index or the percentage of SD bridge at the end of analysis year to the current condition (92.1 for health index and 0 of SD bridge), we cannot conclude that the estimated current budget is over-investing. All these limitations need to be recognized when using the results. The results presented here are intended to facilitate discussion and provide tools to understand the tradeoffs, costs and consequences of various asset management decisions.

## 6. Conclusions and discussions

This project has established the framework that utilizes DEA and current available tools - HERS-ST, PONTIS, and Asset Manager-NT - to help decision makers make more efficient investments within and cross-assets. The analysis demonstrates that multiple performance measures can be integrated into the decision-making process without having to explicitly assign weights. Planning for the management of the highway network can then be addressed in a systematic way that recognizes the tradeoffs among different funding periods and objectives such as preserving existing investments, safety, roughness and user costs.

This paper answers this question by using tools currently available within highway agencies, such as HERS-ST and the DEA method, to select the most efficient highway investment alternatives. Even though the method is mathematical in nature, the theory behind is straightforward and can be easily implemented in highway agencies using a spreadsheet, and thus is currently ready for implementation at the practice level.

Meanwhile, this case study underscores the importance of good data, but also emphasizes the limitations of the tools. HERS-ST does not have good pavement deterioration models

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and many of the recommended actions are not relevant to interstate highways. PONTIS only uses the direct cost to perform maintenance actions and does not include indirect costs. We also see the challenges involved in integrating risk into the decision-making process. However, the case study has demonstrated that the pavement and bridge data is easily available and can be assembled in a format that can be used to understand the tradeoffs and the relative importance of different performance measures. The results presented here are intended to facilitate discussion and provide tools to understand the tradeoffs, costs and consequences of various asset management decisions.

Just like any decision-making approach has its applicability and limitations, acknowledging both advantages and disadvantages will help decision makers wisely utilize the DEA method for asset management. DEA can be a powerful tool to handle multiple input and multiple output models, without any assumption of functional form relating inputs to outputs. DMUs can be directly compared against a peer or combination of peers, despite the fact that inputs and outputs can have very different units. Meanwhile, an analyst should keep the limitations of DEA in mind when choosing to use DEA. First, since DEA is an extreme point technique, noise (such as measurement error, the selection of DMUs for benchmarking) can be sensitive to the benchmarking results. Second, as a nonparametric technique, DEA is robust in estimating “relative” efficiency of a DMU comparing to its peers, but it converges relatively slowly to “absolute” efficiency, or the “theoretical maximum”. In addition, since DEA creates a separate linear programming problem for each DMU, complex problems can be computationally intensive.

## Conflict of interest

The authors do not have any conflict of interest with other entities or researchers.

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## REFERENCES

Adey, B.T., 2017. A process to enable the automation of road asset management. In: The 2nd International Symposium on Infrastructure Asset Management (SIAM), Zurich, 2017.

American Association of State Highway and Transportation Officials (AASHTO), 2010. AASHTOWare 2010 Catalog. PONTIS. AASHTO, Washington DC.

American Association of State Highway and Transportation Officials (AASHTO), 2011. AASHTO Transportation Asset Management Guide: a Focus on Implementation. AASHTO, Washington DC.

Bai, Q., Anwaar, A., Li, Z., et al., 2015. A hybrid Pareto frontier generation method for trade-off analysis in transportation asset management. Computer-Aided Civil and Infrastructure Engineering 30 (3), 163–180.

Bai, Q., Labi, S., Sinha, K.C., 2011. Trade-off analysis for multiobjective optimization in transportation asset management by generating Pareto frontiers using extreme points nondominated sorting genetic algorithm II. Journal of Transportation Engineering 138 (6), 798–808.

Barnum, D.T., Coupet, J., Gleason, J., et al., 2016. Impact of input substitution and output transformation on data envelopment analysis decisions. Journal of Applied Economics 49 (15), 1543–1556.

Barnum, D.T., McNeil, S., Hart, J., 2007. Comparing the efficiency of public transportation subunits using data envelopment analysis. Journal of Public Transportation 10 (2), 1–16.

Barnum, D.T., Tandon, S., McNeil, S., 2008. Comparing the performance of bus routes after adjusting for the environment using data envelopment analysis. Journal of Transportation Engineering 134 (2), 77–85.

Cambridge Systematics, Inc., 2005. Analytical Tools for Asset Management. NCHRP Report 545. Transportation Research Board, Washington DC.

Cambridge Systematics, Inc., 2006. Performance Measures and Targets for Transportation Asset Management. NCHRP Report 551. Transportation Research Board, Washington DC.

Cambridge Systematics, Inc., 2009. An Asset-Management Framework for the Interstate Highway System. NCHRP Report 632. Transportation Research Board, Washington DC.

Camp, R.C., 1995. Business Process Benchmarking: Finding and Implementing Best Practices. ASQC Quality Press, Milwaukee.

Chan, W.T., Fwa, T.F., Tan, J.Y., 2003. Optimal fund-allocation analysis for multidistrict highway agencies. Journal of Infrastructure Systems 9 (4), 167–175.

Charnes, A., Clark, C.T., Cooper, W.W., et al., 1985. A developmental study of data envelopment analysis in measuring the efficiency of maintenance units in U. S. air forces. Annals of Operations Research 2 (1), 95–112.

Cooper, W.W., Seiford, L.M., Tone, K., 2006. Data Envelopment Analysis: a Comprehensive Text with Models, Applications, References and DEA-Solver Software, second ed. Springer, Boston.

Cooper, W.W., Seiford, L.M., Zhu, J., 2011. Handbook on Data Envelopment Analysis. Springer, Boston.

Cowe, L.C., Haas, R., Tighe, S., 2006. Asset service index as integration mechanism for civil infrastructure. Transportation Research Record 1957, 1–7.

Dehghanisanij, M., Flintsch, G.W., Flintsh, A.M., 2010. A flexible framework for sustainable multi-objective cross-asset infrastructure management. In: The 89th Annual Meeting of the Transportation Research Board, Washington DC, 2010.

Federal Highway Administration (FHWA), 2005. HERS-ST: Highway Economic Requirements Systems - State Version: Technical Report. FHWA, Washington DC.

Flintsch, G.W., Bryant Jr., J.W., 2006. Asset Management Data Collection for Supporting Decision Processes. Office of Asset Management. Federal Highway Administration (FHWA), Washington DC.

Fwa, T.F., Farhan, J., 2012. Optimal multiasset maintenance budget allocation in highway asset management. Journal of Transportation Engineering 138 (10), 1179–1187.

Gharaibeh, N.G., Chiu, Y.C., Gurian, P.L., 2006. Decision methodology for allocating funds across transportation infrastructure assets. Journal of Infrastructure Systems 12 (1), 1–9.

Gharaibeh, N.G., Darter, M.I., Uzarski, D.R., 1999. Development of prototype highway asset management system. Journal of Infrastructure Systems 5 (2), 61–68.

Jani, S., 2007. Road asset valuation and management-case study Finland. In: International Seminar on Sustainable Road Financing and Investment, Arusha, 2007.

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Kuhn, K.D., 2010. Network-level infrastructure management using approximate dynamic programming. Journal of Infrastructure Systems 16 (2), 103–111.

Li, Q., McNeil, S., Rahimian, S., 2011. Assessments of highway investment objectives based on data envelopment analysis (DEA). In: The 90th Annual Meeting of the Transportation Research Board, Washington DC, 2011.

Li, Z., Sinha, K.C., 2004. Methodology for multicriteria decision making in highway asset management. Transportation Research Record 1885, 79–87.

Li, Z., Sinha, K.C., 2009. Application of Shackle's model and system optimization for highway investment decision making under uncertainty. Journal of Transportation Engineering 135 (3), 129–139.

Li, Z., Kaul, H., Kapoor, S., et al., 2012. New methodology for transportation investment decisions considering project interdependencies. Journal of Transportation Research Record 2285, 36–46.

Liang, L., Yang, F., Cook, W.D., et al., 2006. DEA models for supply chain efficiency evaluation. Annals of Operations Research 145 (1), 35–49.

McNeil, S., Li, Q., 2012. Advancing Asset Management at DelDOT. Final Report. University of Delaware, Newark.

McNeil, S., Mizusawa, D., Nathman, R., et al., 2008. Asset Management as a Strategic Decision-Making Tool in DelDOT. Final Report. Delaware Center for Transportation, Newark.

McWilliams, A., Parhankangas, A., Coupet, J., et al., 2014. Strategic decision making for the triple bottom line. Business Strategy and the Environment 25 (3), 193–204.

Mrawira, D., Amador, L., 2009. Cross-assets trade-off analysis: why are we still talking about it? In: The 88th Annual Meeting of the Transportation Research Board, Washington DC, 2009.

Organization for Economic Cooperation and Development (OECD), 2001. Asset Management for the Roads Sector. OECD Publications Service, Paris.

Ozbek, M.E., de la Garza, J.M., Triantis, K., 2009. Data envelopment analysis as a decision-making tool for transportation professionals. Journal of Transportation Engineering 135 (11), 822–831.

Ozbek, M., de la Garza, J.M., Triantis, K., 2010a. Data and modeling issues faced during the efficiency measurement of road maintenance using data envelopment analysis. Journal of Infrastructure Systems 16 (1), 21–30.

Ozbek, M., de la Garza, J.M., Triantis, K., 2010b. Efficiency measurement of bridge maintenance using data envelopment analysis. Journal of Infrastructure Systems 16 (1), 31–39.

Pagano, A.M., McNeil, S., Ogard, E., 2005. Linking asset management to strategic planning processes: best practices from state departments of transportation. Transportation Research Record 1924, 184–191.

Sadek, A.W., Kvasnak, A., Segale, J., 2003. Integrated infrastructure management systems: small urban area's experience. Journal of Infrastructure Systems 9 (3), 98–106.

Sirirangsi, P., Amekudzi, A., Herabat, P., 2003. Capturing effects of maintenance practices in highway asset valuation: replacement-cost approach versus book-value method. Transportation Research Record 1824, 57–65.

Small, E.P., Swisher, M., 2000. Integration of Bridge and Pavement Management Systems: a Proposed Strategy for Asset Management. Transportation Research Circular 498. Transportation Research Board, Washington DC.

Taggart, A., Tachtsi, L., Lugg, M., et al., 2014. UKRLG framework for highway infrastructure asset management. Infrastructure Asset Management 1 (1), 10–19.

Wanke, P., Barros, C.P., Figueiredo, O., 2016. Efficiency and productive slacks in urban transportation modes: a two-stage SDEA-Beta regression approach. Utilities Policy 41, 31–39.

Wu, Z., Flintsch, G.W., 2009. Pavement preservation optimization considering multiple objectives and budget variability. Journal of Transportation Engineering 135 (5), 305–315.

Wu, Z., Flintsch, G.W., Ferreira, A., et al., 2012. Framework for multiobjective optimization of physical highway assets investments. Journal of Transportation Engineering 138 (12), 1411–1421.

Zhang, Z., Agbelie, B.R., Labi, S., et al., 2015. Efficiency measurement of bridge management with data envelopment analysis. Transportation Research Record 2481, 1–9.

Zhang, Z., Aki, F., Hudson, W.R., 2002. Developing an Integrated Management System for the Urban Transportation Infrastructure. SWUTC/02/167511-1. Center for Transportation Research, University of Texa at Austin, Austin.

Zhu, J., 2009. Quantitative Models for Performance Evaluation and Benchmarking: Data Envelopment Analysis with Spreadsheets, second ed. Springer, Boston.

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