MEASURING THE BENEFITS OF IMPLEMENTING ASSET MANAGEMENT SYSTEMS AND TOOLS

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<tr><td colspan="4">16. Abstract
Although transportation agencies in the U.S. have been developing Asset Management Systems (AMS) for specific types of infrastructure assets, there are several barriers to the implementation of AMS. In particular, implementation and development costs are critical issues. Without showing that AMS implementation improves asset performance and that the benefits of AMS implementation outweigh the costs for AMS implementation and operation, further implementation and development will not occur. This paper documents the development of a generic methodology for quantifying the benefits derived from implementation of AMS and justifying investment in AMS implementation. The generic methodology involves three analysis methods: descriptive analysis, regression analysis, and benefit-cost analysis. These methods draw on basic principles of engineering economic analysis and apply to two types of evaluations: an ex post facto evaluation and an ex ante evaluation depending on the time frame and the availability of time series data. While the concepts are relatively simple, the challenge lies in identifying data to support the application of the methodology. This paper demonstrates how the methodology can be applied to evaluate the implementation of a pavement management system in terms of efficacy, effectiveness, and efficiency (3Es).</td></tr>
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LIST OF ABBREVIATIONS

AADT	Annual Average Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
AHS	Automated Highway System
ALS	Area Licensing Scheme
AMS	Asset Management Systems
APC	Average Pavement Condition
AVL	Automated Vehicle Location
BCA	Benefit-Cost Analysis
BCR	Benefit-Cost Ratio
BHI	Bridge Health Index
BMS	Bridge Management Systems
CMP	Pavement Composite Index
dTIMS™ CT	Deighton Total Infrastructure Management System
DOT	Department of Transportation
ESAL	Equivalent Single Axle Loads
ETC	Electronic Toll Collection
FHWA	Federal Highway Administration
FRT	First Registration Tax
GASB	Governmental Accounting Standard Board Statement
GIS	Geographic Information System
GLS	Generalized Least Squares
HDM	Highway Design and Maintenance Standard Model
HERS-ST	Highway Economic Requirement System – State Version
HPMS	Highway Performance Monitoring System
ISTEA	Intermodal Surface Transportation Efficiency Act
ITS	Intelligent Transportation Systems
IRI	International Roughness Index
IRR	Internal Rate of Return
LRT	Light Rail Transit
LTAP	Local Technical Assistance Programs
M&R	Maintenance and Rehabilitation
NPV	Net Present Value

LIST OF ABBREVIATIONS (CONTINUED)

OECD	Organisation for Economic Co-operation and Development
OLS	Ordinary Least Squares
OMB	Office of Management and Budget
PCI	Pavement Condition Index
PIARC	World Road Association
PMS	Pavement Management Systems
PSR	Pavement Serviceability Rating
PQI	Pavement Quality Index
SSM	Soft Systems Methodology
STIP	Statewide Transportation Improvement Plan
TFP	Total Factor Productivity
TRB	Transportation Research Board
TWAPC	Traffic Weighted Average Pavement Condition
VKT	Vehicle Kilometers Traveled
VMT	Vehicle Miles Traveled
VTrans	Vermont Agency of Transportation

EXECUTIVE SUMMARY

Although transportation agencies in the U.S. have been developing Asset Management Systems (AMS) for specific types of infrastructure assets, there are several barriers to the implementation of AMS. In particular, implementation and development costs are critical issues. Without evidence of AMS benefits, further implementation and development of AMS may be constrained. This research report documents the development of a generic methodology for quantifying the benefits derived from implementation of AMS and justifying investment in AMS implementation. The generic methodology involves three analysis methods: descriptive analysis, regression analysis, and benefit-cost analysis. These methods draw on basic principles of engineering economic analysis and apply to two types of evaluations: an *ex post facto* evaluation and an *ex ante* evaluation depending on the time frame and the availability of time series data. While the concepts are relatively simple, the challenge lies in identifying data to support the application of the methodology. This research demonstrates how the methodology can be applied to evaluate the implementation of a pavement management system in terms of efficacy, effectiveness, and efficiency (3Es).

1. Introduction

Asset management systems (AMS) are tools designed to support the systematic process of cost-effectively maintaining, upgrading, and operating physical assets. Such systems include asset inventory, condition assessment and performance modeling, alternative selection and evaluation of maintenance and rehabilitation strategies, methods for evaluating the effectiveness of each strategy, project implementation, and performance monitoring. AMS provide an integrated approach to strategic decision-making, and may combine different management elements such as pavement management systems (PMS) and bridge management systems (BMS). Also, AMS support consistent evaluation and allow agencies to trade off investment across the different elements. Furthermore, AMS help agencies to understand the implications of different investment options (Cambridge Systematics et al. 2005).

After an agency implements AMS, appropriate maintenance and rehabilitation (M&R), identified using the decision-support tools, including condition prediction models and economic analysis tools in the AMS, improves asset performance and reduce M&R costs simultaneously. Also, user and external (non-user) costs are reduced because appropriately maintained roads provide a better driving environment for users, thus reducing operating costs, crash costs, travel time costs, and environmental impacts.

The report addresses asset management issues and then develops the generic methodology for evaluating AMS implementation based on commonly available data. A case study using the Federal Highway Administration's Highway Economic Requirements – State Version (HERS-ST) is then developed and the results discussed. Finally conclusions are drawn.

2. Background

Although transportation agencies in the U.S. have been developing AMS for specific types of infrastructure assets, there are several barriers to implementing AMS. The barriers can prevent agencies from successful AMS implementation. Successful implementation is defined as the continual use of AMS to support decision making, achievement of performance goals defined by agencies, and production of larger benefits (e.g., reduction of agency and user costs) than costs for AMS implementation and operation (Mizusawa and McNeil 2006).

The cost of implementation and development of AMS is an especially critical issue. Without evidence of AMS benefits, further implementation and development of AMS may be constrained. In particular, upper-level managers are interested in benefits that can be translated into monetary values (Smadi 2004), because they need to justify their investment in AMS. Also, agencies that have already implemented AMS may require justification of past and continued investment in AMS. Therefore, it is imperative to quantify the benefits of AMS implementation and demonstrate that the benefits exceed the implementation and operating costs in order to disseminate and implement AMS in agencies.

This report presents a generic methodology for quantifying the benefits derived from implementation of AMS and justifying investment in AMS implementation. The methodology draws on concepts of engineering economic analysis. While the concepts are relatively simple, the challenge lies in assembling the data to support the application of the methodology. Most importantly, the specifics of the methodology are linked to the particular types of data identified for analysis. While the cultural change required to implement asset management in an organization is equally important, such change is beyond the scope of this project.

3. Generic Methodology

Since pavement management is a significant activity and pavements account for up to 60 percent of the total assets in a typical agency in the U.S. (Flintsch et al. 2004), we will focus on pavement management as one element of asset management. In this section, we present the basic types of evaluation, the components of the generic methodology, and the concepts of efficacy, effectiveness and efficiency (3Es). The methodology is driven by the types of data either available or that can be generated and the relevant analysis tools.

Evaluation Design

There are two types of evaluation design: an *ex post facto* and *ex ante*, determined by the implementation of PMS and the availability of time series data related to pavement management. The data include performance measures such as pavement conditions, traffic conditions, and emissions. Using measures responding to agency's performance goals is recommended. Since PMS is implemented by an agency that manages a network, we focus on performance at the network level. A comparison of individual sections is not only meaningless but any data is both spatially and temporally correlated.

An *ex post facto* or retrospective evaluation is applied to agencies that have already implemented PMS. Meanwhile, an *ex ante* or prospective evaluation is applied to agencies that are going to implement PMS. Figure 1 shows the concepts of the *ex post facto* and *ex ante* evaluations. The *ex post facto* evaluation includes two types: a comparison of actual performances, such as pavement condition, before and after PMS implementation (left hand side); and a comparison between predicted performance if PMS had not been implemented and actual performance after PMS implementation (center). Similar to the analyses of Hudson et al.

(2001), and Cowe Falls and Tighe (2004), the first type observes trends in pavement condition using time series data to compare differences before and after PMS implementation. The second type needs time series data of the actual pavement condition both before and after PMS implementation as well. The actual pavement condition before PMS implementation is used to predict pavement condition without PMS after the year of PMS implementation based on a strategy used before PMS implementation (e.g., a worst first) and to compare this to the actual pavement condition with PMS after PMS implementation. This type includes the analysis by Smadi (2004). The improvement in the pavement conditions before and after PMS implementation (left hand side) and with and without PMS implementation (center) represents the benefits of PMS implementation in terms of asset performance. Because the benefits accrue over years and are not shown immediately after PMS implementation, it is necessary to consider what an appropriate analysis period is in the analysis.

Since the time series data required for the *ex post facto* evaluation are rarely available in transportation agencies, we need an alternative evaluation method. That is the *ex ante* evaluation depicted in the right hand side in Figure 1. Using current performance data, two different future performances are predicted based on strategies: ‘without’ PMS implementation (e.g., a worst first strategy) and ‘with’ PMS implementation (i.e., a PMS optimization strategy). In addition, since future pavement conditions can be simulated based on the strategies, the *ex ante* evaluation can analyze the benefits of PMS implementation even if an agency had not implemented PMS. Although the predicted conditions do not represent real pavement condition, they can show the difference in pavement condition between ‘with’ and ‘without’ cases, that is, the benefits of PMS implementation. As demonstrated, the *ex ante* evaluation is similar to the *ex post facto* evaluation using a ‘with and without’ comparison in Figure 1 that compares predicted conditions without PMS implementation to actual conditions after PMS implementation. This is a quasi evaluation design recognizing the benefits of PMS between ‘with’ and ‘without’ cases.

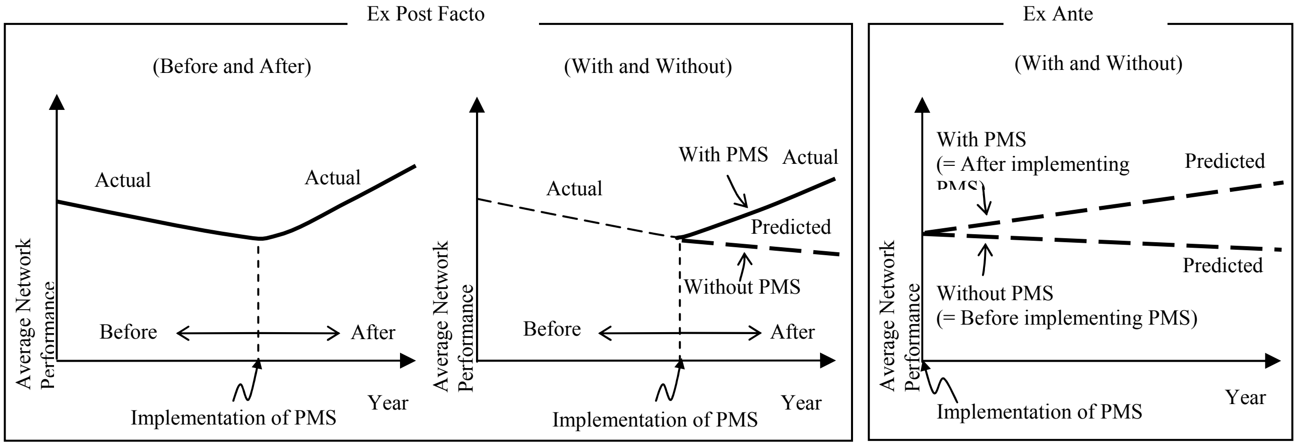

Figure 1. Concepts of *Ex Post Facto and Ex Ante* Evaluations

As described, the evaluation type is determined by analyzing whether PMS is already implemented and whether time series data are available before and after PMS implementation. Figure 2 depicts the flow diagram showing the process for quantifying the benefits of PMS implementation and justifying investment in PMS implementation.

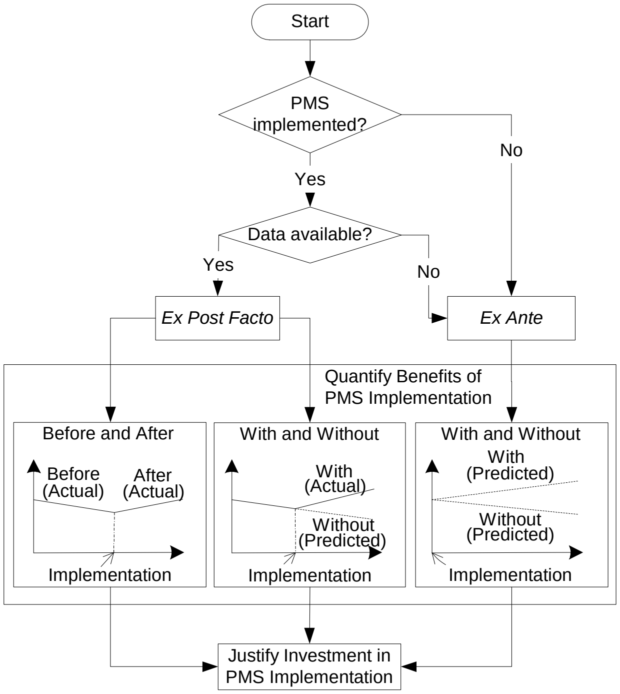

Figure 2. Flow Diagram

Benefit Quantification

Once we choose the evaluation design based on either the *ex post facto* evaluation or *ex ante* evaluation, we compare performance 'before' and 'after,' or 'with' and 'without' PMS implementation. The comparison shows the differences in performance, which represent the benefits of PMS implementation. The benefits can be quantified by three analysis methods: a descriptive analysis based on common performance measures that capture improvements due to PMS implementation in terms of traffic and asset conditions; a regression analysis intended to quantify the contribution of PMS implementation to improved performance; and a benefit-cost analysis (BCA) to quantify monetary values of the benefits and costs of PMS and compare the benefits to the costs. The descriptive analysis and regression analysis can analyze various benefits of AMS implementation identified by Mizusawa and McNeil (2005) by using creative performance measures (e.g., degree of customer satisfaction in using improved assets), while BCA analyzes only benefits that can be monetized.

Descriptive Analysis

Recognizing the trends in an agency's performance (e.g., pavement condition, budget, and expenditure), and exogenous effects (e.g., economy, traffic volume, and environment) in the context of an agency's profile (types of assets, organizational structure, presence of legislation, and PMS) is an important first step. The descriptive analysis can show various trends using performance measures comparing before and after PMS implementation based on the ex post facto evaluation, or between with and without PMS implementation based on the ex ante evaluation.

One performance measure, the traffic weighted average pavement condition by year (Eq. (1)), can be used to capture one of the agency's performance measures – pavement condition.

Also, this measure can illustrate users' comfort in terms of riding quality, if pavement condition ratings focusing on surface characteristics, such as International Roughness Index (IRI) and Present Serviceability Rating (PSR) are used.

$$\text{Traffic Weighted Average Pavement Condition} = \frac{\sum_{i=1}^{n}(PCI_i \times AADT_i \times Length_i)}{\sum_{i=1}^{n}(AADT_i \times Length_i)} \qquad i = 1,\ldots, n \qquad (1)$$

where *PCI* = pavement condition index in section *i*; *AADT* = annual average daily traffic in section *i*; and *Length* = length of road sections in mile in section *i*. This measure can be plotted by year. Differences between before and after conditions, or between with and without conditions, can be illustrated visually. Summary statistics, for example, the average measurement value over a fixed analysis period can also be examined.

Regression Analysis

Using the network level performance measures developed for the descriptive analysis, regression analysis can be performed to address the weaknesses of the descriptive analysis, specifically, the inability to consider various changes simultaneously. This analysis is intended to observe the degree of independent variables' influences on a dependent variable represented by the independent variables' coefficients.

There are three components to the analysis: 1) Find an appropriate dependent variable representing the productivity of the investment in the PMS. We can assume productivity is an increase of PCI, increase of pavement life, reduction of M&R costs, and so on. It is necessary to explore various measures and determine an appropriate one. 2) Identify independent variables. 3) Determine a type of regression model. Among many types such as linear, polynomial, log linear, and so on, we should determine the best type by measure of fit (i.e., R-Square). We can also evaluate the statistical significance of the independent variables using t-values. An example of a liner regression model using 'with and without' data based on the *ex post facto* and *ex ante* evaluations is as follow:

Let $TWAPC_t$ be the traffic weighted average pavement condition in year *t* (Eq. (1)), X_{tn} be the vectors of *n* independent variables (e.g., AADT, length, M&R treatment costs) in all road sections in year *t*, and PMS_t be the use of PMS in year t. The model to be estimated is:

$$TWAPC_t = \beta_0 + \beta_1 x_{t1} + \beta_2 x_{t2} + \ldots + \beta_n x_{tn} + \delta_t PMS_t + \varepsilon_t \qquad t = 1,\ldots, \mathrm{T} \qquad (2)$$

where $\beta_0, \beta_1, \ldots, \beta_n$ = coefficients; δ_t = a coefficient for the dummy variable, PMS_t (i.e., δ_t is equal to 1 if PMS is used in year t and equal to 0 otherwise); and ε_t = error term associated with the traffic weighted average pavement condition in year t. The dummy variable PMS_t indicates the impact of the use of PMS on the traffic weighted average pavement condition. If the coefficient of the variable is a positive value, PMS implementation improves the value of the traffic weighted average pavement condition (i.e., benefits).

When 'before and after' data based on the *ex post facto* evaluation are used, the traffic weighted average pavement conditions before and after PMS implementation do not align with the same analysis period. Hence, a linear regression without a dummy variable is used, and we can estimate the coefficients of the independent variables for 'before' and 'after' cases and compare them to each other. The differences in the comparison might be caused by PMS implementation. Because other implicit effects may cause the differences, we may not be able to determine the exact impact of PMS implementation on the traffic weighted average pavement condition as the dummy variable in Eq. (2) performs.

To build the models at the network level, time series data including pavement conditions and various measures, such as AADT, length, and M&R treatment costs, in all road sections are required. An ordinary least squares (OLS) regression is used to build the models, as the traffic weighted average pavement condition can be assumed to be independently and identically distributed.

Benefit-Cost Analysis

BCA is employed to show agency, user, and external benefits using monetary values. BCA uses alternatives for which benefits and costs can be measured in relative terms. Usually, each alternative addresses benefits produced by a project and costs incurred by the project. An important element of BCA is determining the perspective from which to conduct the analysis. As highway agencies provide a service, the analysis must be conducted from a social welfare perspective, which recognizes the benefits to drivers. However, it is difficult to quantify the benefits of the service, because the drivers do not directly pay for the service as they do for a utility such as water. Hence, the benefits are most conveniently measured as incremental or relative benefits between a base case and 'before' case or 'after' case, or between a base case and 'without' case or 'with' case. A base case can be do-nothing (i.e., not adopting pavement management). The base case and the cases with adoption of pavement management are assumed to be mutually exclusive.

The comparison of two alternatives, 'before' and 'after' cases, or 'with' and 'without' cases, can quantify the benefits of PMS implementation using the benefits derived from pavement management compared to the base case and initial costs for M&R for each alternative. In order to compare two alternatives, we need to identify benefits and costs related to pavement management. As Hudson et al. (2001) and Cowe Falls and Tighe (2004) demonstrated, benefits and costs for before and after PMS implementation, or without and with PMS implementation, are required. **Table** 1 lists the benefits and costs related to pavement management used for benefit quantification. Although there is a wide spectrum of qualitative benefits of PMS implementation (Cowe Falls and Tighe 2004; Haas et al. 1994; Litzka et al. 2000; Smadi 2004; Sztraka 2001), we use the benefits that can be monetized.

The year-by-year benefits and costs (known as the cash flow) listed in Table 1 are estimated over the analysis period (Hendrickson and Wohl 1984). To estimate the benefits and costs for each alternative, we define:

- $B_{x,t}$ = expected agency, user, and external benefits from alternative x during year t
- $C_{x,t}$ = expected initial costs for M&R treatments for alternative x during year t

Table 1. BENEFITS AND COSTS

Category		Description	Benefit Quantification	Investment Justification
Benefits	Agency	• Reduction in the cost of M&R	X	X
	User	• Savings in user costs, including travel time cost, vehicle operating cost, safety cost	X	X
	External (non-user)	• Reduction in environmental costs, which are subjected to non-user	X	X
Costs	Agency	• Initial costs for M&R treatments	X	X
		• Costs for PMS implementation, including system price and overhead for system development and operation. The system includes database and analysis tools		X

The alternative *x* takes into account the ‘before’ and ‘after’ cases, or ‘without’ and ‘with’ cases, which already take into account incremental benefits derived from the comparison with the base case. Also, two other pieces of information must be specified:

- The analysis period, *n*: the mutually exclusive alternatives must be analyzed for the same and concurrent analysis period to take into account the benefits and costs. The length of the analysis period depends on: 1) the expected life of an asset management project, and 2) the period in which we can fairly reliably predict benefits and costs (Hendrickson and Wohl 1984). It is necessary to decide the appropriate analysis period, since it is assumed that benefits and costs accrue over years.
- The discount rate, expressed in decimal form, *i*: although the benefits and costs arise from different sources and are accrued or increased in different time periods throughout the analysis period, we need to consider them at the same time in BCA. Since the monetary value changes over the analysis period, we have to set not only the specific time when we analyze the benefits and costs, but also the values of the benefits and costs to a consistent (discounted) monetary value using a discount rate. In order to determine the discount rate, we can refer to the rate of return on money markets or the rate for all projects being considered by a decision-making unit such as the Office of Management and Budget (OMB) and the Congressional Budget Office (Weimer and Vining 2004).

To quantify the benefits of PMS implementation, either the Net Present Value (NPV) Method or the Benefit-Cost Ratio (BCR) Method can be used (Hendrickson and Wohl 1984). Here, we review the NPV Method.

First, the stream of benefits and costs are discounted to their present value and then netted to determine the net present value. For alternative ‘before’ and ‘after’ cases based on the ex post facto evaluation, the net present values for the n-year analysis period when the interest rate is the *i* or [*NPVbeforePMS,n*]*i* and [*NPVafterPMS,n]i* would be:

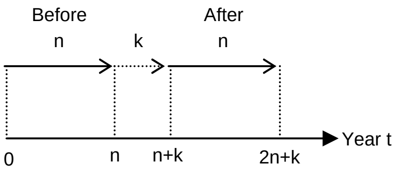

Figure 3. Relationship of Analysis Periods

Before: $[NPV_{beforePMS,n}]_i = [TPVB_{beforePMS,n}]_i - [TPVC_{beforePMS,n}]_i =$

$$\sum_{t=0}^{n} \frac{B_{beforePMS,t}}{(1+i)^t} - \sum_{t=0}^{n} \frac{C_{beforePMS,t}}{(1+i)^t} = \sum_{t=0}^{n} \frac{B_{beforePMS,t} - C_{beforePMS,t}}{(1+i)^t} \tag{3}$$

After: $[NPV_{afterPMS,\mathrm{n}}]_i = [TPVB_{afterPMS,n}]_i - [TPVC_{afterPMS,n}]_i =$

$$\sum_{t=n+k}^{2n+k} \frac{B_{afterPMS,t}}{(1+i)^{t-(n+k)}} - \sum_{t=n+k}^{2n+k} \frac{C_{afterPMS,t}}{(1+i)^{t-(n+k)}} = \sum_{t=n+k}^{2n+k} \frac{B_{afterPMS,t} - C_{afterPMS,t}}{(1+i)^{t-(n+k)}} \tag{4}$$

where $[\mathrm{TPVB}_{x,\alpha}]_i$ = total discounted benefits of alternative x for an α-year period and discount rate i; $[\mathrm{TPVC}_{x,\alpha}]_i$ = total discounted costs of alternative x for an α-year period and discount rate i; and k = a period between 'before' and 'after' cases (k ≥ 1). The relationship between the three analysis periods of 'before k,' 'after k,' and period k, is drawn in Figure 3. The analysis periods of 'before' and 'after' begin at different years (i.e., the period of 'after' {t| n+k ≤ t ≤ 2n+k} follows that of 'before' {t| 0 ≤ t ≤ n}). PMS is implemented in year n+k-1. As discussed in Hudson et al. (2001), a longer period of k makes it easier to distinguish significant benefits between 'before' and 'after' cases. We note that other authors have used k=0, but this may lead to double counting.

Using Eq. (3) and (4), we calculate net present values for the alternatives and then compare them. That is, [NPVafterPMS,n]i – [NPVbeforePMS,n]i should be greater than zero. Since the before and after analysis does not use mutually exclusive alternatives as the investments are sequential, this analysis is approximate.

For the 'with' and 'without' cases based on the ex post facto and ex ante evaluation, the net present value for the n-year analysis period with discount rate i ([NPVwithPMS,n]i and [NPVwithoutPMS,n]i) is:

Without: $[\mathrm{NPV}_{\mathrm{withoutPMS,n}}]_{\mathrm{i}} = [\mathrm{TPVB}_{\mathrm{withtoutPMS,n}}]_{\mathrm{i}} - [\mathrm{TPVC}_{\mathrm{withoutPMS,n}}]_{\mathrm{i}} =$

$$\sum_{t=0}^{n} \frac{B_{withoutPMS,t}}{(1+i)^t} - \sum_{t=0}^{n} \frac{C_{withtoutPMS,t}}{(1+i)^t} = \sum_{t=0}^{n} \frac{B_{withoutPMS,t} - C_{withoutPMS,t}}{(1+i)^t} \tag{5}$$

With: $[\mathrm{NPV}_{\mathrm{withPMS,n}}]_{\mathrm{i}} = [\mathrm{TPVB}_{\mathrm{withPMS,n}}]_{\mathrm{i}} - [\mathrm{TPVC}_{\mathrm{withPMS,n}}]_{\mathrm{i}} =$

$$\sum_{t=0}^{n} \frac{B_{withPMS,t}}{(1+i)^t} - \sum_{t=0}^{n} \frac{C_{withPMS,t}}{(1+i)^t} = \sum_{t=0}^{n} \frac{B_{withPMS,t} - C_{withPMS,t}}{(1+i)^t} \tag{6}$$

Using Eq. (5) and (6), the difference in net present values [NPVwithPMS,n]i – [NPVwithoutPMS,n]i is computed. Because the benefits and costs of 'with' and 'without' cases arise in the same time period, the analysis period, n, is considered. If the difference in the net present values either between ‘before’ and ‘after’ cases or between ‘with’ and ‘without’ cases is positive, PMS implementation is beneficial.

Investment Justification

Given the quantified agency, user, and external benefits of pavement management and costs for M&R treatments by BCA in the benefit quantification, it is possible to justify investment in PMS implementation using BCA. BCA uses the incremental benefits of pavement management between ‘before’ and ‘after’ cases, or between ‘with’ and ‘without’ cases, and the costs for PMS implementation, and then directly analyzes whether investment in PMS implementation is justifiable. The last column of **Table** 1 lists the benefits and costs related to PMS implementation used for investment justification. This column differs from the column for the benefit quantification as the costs for PMS implementation are included.

Once the benefits and costs are specified, we need to conduct BCA using the NPV Method or the BCR Method. Again, we focus on the NPV method and extend Eq. (3) and (4) using the incremental benefits derived from ‘before’ and ‘after’ cases based on the *ex post facto* evaluation as follows:

$$[NPV_{PMS,n}]_i = \{([TPVB_{afterPMS,n}]_i - [TPVC_{afterPMS,n}]_i) - ([TPVB_{beforePMS,n}] - [TPVC_{beforePMS,n}]_i)\}$$

$$- [TPVC_{PMS,n}]_i$$

$$= \left\{ \sum_{t=n+k}^{2n+k} \frac{B_{afterPMS,t} - C_{afterPMS,t}}{(1+i)^{t-(n+k)}} - \sum_{t=0}^{n} \frac{B_{beforePMS,t} - C_{beforePMS,t}}{(1+i)^{t}} \right\} - \sum_{t=0}^{2n+k} \frac{C_{PMS,t}}{(1+i)^{t}} \qquad (7)$$

where $[TPVC_{PMS,n}]_i$ = total discounted costs of PMS implementation for an n-year period and discount rate i. the last term recognizes that the PMS implementation costs may occur at any time during the analysis period but they must be discounted to be consistent with the ‘after’ benefits and costs. Since the analysis periods are different from each other, this ‘before and after’ comparison violates the rule of consistent analysis periods. Hence, this comparison uses approximate benefits and costs to justify investment similar to that conducted by Cowe Falls and Tighe (2004).

Using the incremental benefits derived from ‘with’ and ‘without’ cases based on the *ex post facto* and *ex ante* evaluations, the net present value for the n-year analysis period with discount rate i is:

$$[NPV_{PMS,n}]_i = \{([TPVB_{withPMS,n}]_i - [TPVC_{withPMS,n}]_i) - ([TPVB_{withoutPMS,n}]_i - [TPVC_{withoutPMS,n}]_i\}$$

$$- [TPVC_{PMS,n}]_i$$

$$= \left\{ \sum_{t=0}^{n} \frac{B_{withPMS,t} - C_{withPMS,t}}{(1+i)^{t}} - \sum_{t=0}^{n} \frac{B_{withoutPMS,t} - C_{withoutPMS,t}}{(1+i)^{t}} \right\} - \sum_{t=0}^{n} \frac{C_{PMS,t}}{(1+i)^{t}} \qquad (8)$$

Because the benefits of ‘with’ and ‘without’ cases and the costs of PMS implementation arise from the same time, only the analysis period, n, is considered. If the net present value of Eq. (7) or (8) (i.e., the monetized benefits of pavement management between ‘after’ and ‘before’ cases, or between ‘with and ‘without’ cases, minus the costs for PMS implementation) is positive, PMS implementation is beneficial; otherwise, it is not beneficial.

Efficacy, Effectiveness and Efficiency: The 3Es

Drawing on work in Soft Systems Methodology (Checkland 1999), we distinguish among different approaches to quantifying the benefits of PMS implementation and justifying investment in PMS implementation, with respect to the 3Es (that is, efficacy, effectiveness, and efficiency) defined as follows:

- Efficacy: shows whether PMS work or not. The efficacy can be recognized by the difference in performance between 'before' and 'after,' or between 'with' and 'without,' using descriptive analysis and regression analysis. Also, the BCA quantifies the efficacy using the net benefits (i.e., benefits including reductions in agency, user, and external costs minus M&R costs), and the ratio of benefits to costs for M&R treatments.
- Effectiveness: identifies the degree to which PMS achieve the agency's asset management goals. Effectiveness is determined by the difference, but needs to be addressed in term of degree. If the degree is addressed, an agency can observe to what extent asset conditions meet their asset management goals compared to the case of 'before' or 'without.' The results of descriptive analysis, regression analysis, and BCA can articulate the effectiveness.
- Efficiency: identifies optimal use of resources using the ratio of output or outcome to input of PMS. Efficiency can be quantified by the comparison of the ratios of benefits to costs for M&R treatments between 'before' and 'after,' or between 'with' and 'without.' If the costs for M&R before and after, or with and without PMS implementation are available, the different ratios of performance (e.g., pavement condition) to the costs between 'before' and 'after,' or between 'with' and 'without,' assess the efficiency of PMS implementation. All three analysis methods are capable of assessing the efficiency.

Three Analysis Methods

The generic methodology embraces the three analysis methods addressed above to obtain richer insight into PMS implementation as shown in Figure 4. The descriptive analysis identifies data consisting of various performance measures. The differences in the performance measures between 'before' and 'after' cases, or between 'with' and 'without' cases, show the benefits of PMS implementation in terms of the 3Es as well as various trends of the agency's performance and exogenous effects. Then the data are entered into the regression analysis and BCA to quantify the benefits of PMS implementation in terms of monetary values, as well as the performance measures. Since the regression analysis and BCA utilize 'before and after,' or 'with and without' data, they are under the umbrella of the descriptive analysis. These analyses also quantify the benefits in terms of the 3Es. Afterwards, the quantified benefits are used for justifying investment in PMS implementation with BCA in terms of efficiency. Since there are pros and cons in each analysis method (Mizusawa and McNeil 2005), it is necessary to take into account how these methods are used, together or independently. The following case study provides an illustration of the mechanism and nuances of manipulating the data to be able to support the analysis.

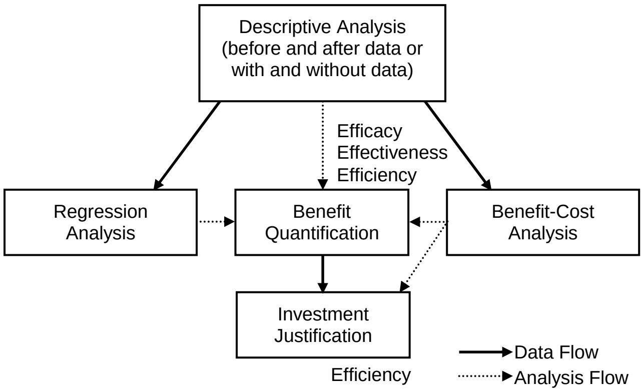

Figure 4. Relationship of Analysis Methodology

4. Case Study

A case study was conducted to apply the generic methodology and evaluate the implementation of Highway Economic Requirement System - State Version (HERS-ST) in terms of benefit quantification and investment justification with respect to the 3Es. HERS-ST, created by the Federal Highway Administration (FHWA), is a highway investment/performance computer model, which determines the impact of alternative highway investment levels and program structures (e.g., widening, resurfacing, and reconstruction) on highway conditions, performance, and agency, user, and external costs. HERS-ST uses data from the Highway Performance Monitoring System (HPMS). HPMS is a national level highway information system, including data related to the extent, conditions, performance, use and operating characteristics of highways (FHWA 2002). This case study uses 2001 HPMS data from the state of New Mexico included in the HERS-ST package (which is downloadable via the FHWA's website). Because the data captures highway inventory and performance in year 2001 only, the comparison of 'with' and 'without' cases based on the *ex ante* evaluation is conducted. A 10-year analysis period from 2001 to 2010 was set.

The highway network included in the HPMS data has 283 sections consisting of rural principal arterials, rural minor arterials, and urban principal arterials. Rural principal arterials are the largest class (66.7% in lane-miles). Rural minor arterials are the second largest functional class (19.9% in lane-miles). Urban principal arterials are smallest among the three classes (13.4 % in lane-miles). The largest portion of the network falls into fair, good, and very good pavement conditions (98.8% in lane-miles) in terms of PSR, which is a subjective pavement rating system based on a scale of 1 to 5.

Using the data, two different scenarios are simulated, a HERS-ST strategy (i.e., 'with' case) and a worst first strategy (i.e., 'without' case). It is presumed that the difference between the two scenarios shows the benefits of HERS-ST implementation in pavement condition. The condition without HERS-ST may simulate the condition before HERS-ST implementation, while the condition with HERS-ST may simulate the condition after HERS-ST implementation.

The two strategies, worst first strategy and HERS-ST strategy, are used by HERS-ST per se to estimate future performances in the 'without' case and the 'with' case, respectively. The worst first strategy focuses only on sections that have deficiencies with respect to deficiency criteria used by HERS-ST and assigns treatments (i.e., do-nothing, resurfacing, and reconstruction) based on the criteria. For example, a section with worse condition and higher AADT is prioritized for treatments. Meanwhile, the HERS-ST strategy assigns the most appropriate treatment that has a highest benefit-cost ratio among potential treatments (i.e., do-nothing, resurfacing, resurfacing with shoulder improvements, resurfacing high-cost lanes, and reconstruction) for each highway section (FHWA 2006).

The 'without' case is developed by overriding treatment recommendations produced by HERS-ST with user-specified treatments that are included in State Improvements data. By making State Improvement data override HERS-ST recommended treatments, a user can analyze the impacts of user-specified treatments compared with those of HERS-ST recommended treatments, with respect to various performance measures. The HERS-ST recommended treatments represents the 'with' case.

5. Results

Following the analysis methods described in the previous section, the benefits of using HERS-ST are assessed using aggregate data as follows:

Benefit Quantification

Using the three analysis methods, the benefits of HERS-ST implementation are quantified in terms of the 3Es as follows:

Descriptive Analysis

HERS-ST runs its analysis for 'with' and 'without' cases while adjusting the 'without' case so that initial investments in improvements are equal to the 'with' case, since the difference in the initial costs between 'with' and 'without' cases was recognized.

Table 2 shows the traffic weighted average pavement condition from 2001 to 2010 for 'with' and 'without' cases. For all road functional classes, the mean with HERS-ST is 0.30 points (=3.67-3.37) higher than that without HERS-ST. The increase is equivalent to 9 % (=0.30/3.37) of the traffic weighted average pavement condition without HERS-ST. Among the three functional classes, rural principal arterials show the highest point increase at 0.35 (=3.82-3.46), while rural minor arterials show the lowest point increase at 0.09 (=3.15-3.05). Hence, HERS-ST maintains stable and good pavement conditions of all functional classes over 10 years.

Table 2. COMPARISON OF TWAPC

			Year		
Case	Functional Class		2001	2005	2010
With HERS-ST	All		3.60	3.74	3.65
	Rural	Principal Arterial	3.79	3.88	3.78
		Minor Arterial	3.56	2.87	3.01
	Urban	Principal Arterial	3.09	3.89	3.71
Without HERS-ST	All		3.60	3.10	3.40
	Rural	Principal Arterial	3.79	3.13	3.48
		Minor Arterial	3.56	2.77	2.83
	Urban	Principal Arterial	3.09	3.25	3.56

The descriptive analysis showed the differences between various performance measures, including the traffic weighted average pavement condition, provided by HERS-ST between the ‘with’ and ‘without’ cases. The differences demonstrate the efficacy – whether HERS-ST works or not, and the effectiveness – how much HERS-ST improves performance such as pavement condition.

Regression Analysis

Regression analysis employed the traffic weighted average pavement condition to capture the benefits of HERS-ST implementation in the network level based on Eq. (2) as follows:

Let $TWAPSR_n$ be the traffic weighted average PSR in funding period n, $AADT_n$ be the total annual average daily traffic in all sections in funding period n, and $HERS_n$ be the use of HERS-ST in funding period n. The model to be estimated is:

$$TWAPSR_n = \beta_0 + \beta_1 AADT_n + \delta_{1n} HERS_n + \varepsilon_n \qquad (9)$$

where β_0 and β_1 = coefficients; δ_{1n} = coefficient for dummy variable (e.g., δ_{1n} is equal to 1 if HERS-ST is used in funding period n and equal to 0 otherwise); and ε_n = error term associated with the n^{th} traffic weighted average PSR. Since there are only six observations (i.e., 3 specific years×2 cases), however, the result is not meaningful from a statistical perspective. If there are enough observations, the coefficient for the dummy variable shows the efficacy and effectiveness of PMS implementation.

Benefit-Cost Analysis

Given the output results of HERS-ST, we found that the ‘with’ case is more efficient in keeping good pavement conditions in the network level, because the ‘with’ case can obtain higher benefits, including agency, user, and external benefits, using almost the same total initial cost as the ‘without’ case. For example, BCR of the ‘with’ case is 7.860, while that of the ‘without” case is 5.282, for all road functional classes over 10 years. Also, the results demonstrate that HERS-ST implementation produces net benefits of $2.0 billion (based on 2004 dollars) over BCA period, because there are differences in the total benefits between ‘with’ and ‘without’ cases. The BCA period corresponds to the duration of treatments’ lives. For example, a simple resurfacing takes one or two funding periods (i.e., 5 to 10 years) as a BCA period. In case of significant treatments, the BCA period can extend beyond the end of the overall analysis period (i.e., 20 years in this case study) (FHWA 2005).

Also, the results imply that HERS-ST implementation results in total net benefits, at least $359 million, over 10 years. This amount does not include the benefits from 2006 to 2010 derived from M&R treatments applied between 2001 and 2005. The benefits consist of $1.5 million agency benefits, $323 million user benefits, and $34.5 million external benefits. These values are based on 2004 dollars. These results demonstrate the efficacy and effectiveness of HERS-ST implementation in terms of monetary values and the efficiency in terms of BCR.

Investment Justification

Given the quantified total discounted benefits of HERS-ST implementation, we can compare the benefits to HERS-ST implementation costs in order to justify investment in HERS-ST implementation. Since there are no available data related to implementation costs, this discussion of whether the benefits exceed HERS-ST implementation costs remains academic. However, using the quantified total benefits, from the point of view of net social welfare, the following statements can be made:

- If an agency spends less than $359 million on implementation over 10 years, the agency can justify the investment in HERS-ST implementation, or
- If an agency spends less than $2.0 billion on implementation over 25 years, the agency can justify the investment in HERS-ST implementation.

From the agency perspective, if the agency spends less that $1.5 million on implementation over 10 years, the agency can justify the investment in HER-ST implementation. Although these net benefit estimates are underestimated, it is not expected that HERS-ST implementation costs would approach $359 million, or even $1.5 million over 10 years, because HERS-ST is a free application distributed by FHWA.

6. Discussion

The results of the case study showed the benefits in pavement conditions between 'with' and 'without' cases. These benefits are due to the fact that different treatments were applied to 46% of the sections in the 'with' case compared to the 'without' case over 10 years.

In the 'with' case, the preventive treatments are applied to about 30% of treatments (i.e., same treatments: 12%, and different treatments: 18%). Figure 5 depicts the decision-making concepts used to determine treatments in the 'with' and 'without' cases with respect to pavement deterioration curves. The horizontal line in the graph shows the treatment threshold between resurfacing and reconstruction in terms of PSR. The 'with' case determines the timing of treatments based on the predicted pavement conditions at the end of a current funding period (FHWA 2005). For example, since the 'with' case can observe the deterioration curve goes below the threshold at year *t* during the five years' funding period based on the predicted pavement condition, the resurfacing that is less expensive than reconstruction is recommended to be conducted at year *t*. Meanwhile, the 'without' case focuses on the initial pavement conditions of the current funding period and thus assumes that resurfacing is not required. Because of the loss of a timely treatment, the pavement condition will degrade continuously. Hence, the 'without' case needs to employ a more aggressive treatment than the 'with' case in order to keep the pavement in good condition; the aggressive treatment overextends the budget for M&R; and the 'without' case loses benefits that are accrued in the 'with' case.

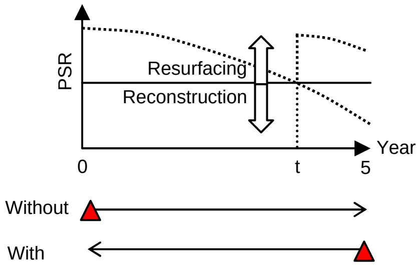

Figure 5. Conceptual Decision-Makings between 'With' and 'Without' Cases

The ‘with’ case considers four types treatment types, while the ‘without’ case considers two treatment types. These different treatment types applied between resurfacing and reconstruction accrues benefits as well. The ‘without’ case has 60 sections or 180 lane-miles of reconstruction, while the ‘with’ case has 16 sections or 17 lane-miles. On the other hand, the ‘with’ case has 104 sections or 617 lane-miles of resurfacing with shoulder improvement, while the ‘without’ case has 15 sections or 122 lane-miles (these are automatically assigned by HERS-ST, although the ‘without’ case does not consider the treatment). It is assumed that the ‘with’ case considers the resurfacing with shoulder improvement as an appropriate treatment type, but not the reconstruction used in the ‘without’ case. Since the unit cost of resurfacing with shoulder improvement is less expensive than that of reconstruction (e.g., 60-70% less expensive in urban principal), the ‘with’ case can treat much more pavements than the ‘without’ case (1.12 times in number of sections; 1.19 times in lane-miles). The ‘with’ case uses less expensive treatments than the ‘without’ case, and allows investment in further treatments.

The generic methodology includes three analysis methods: descriptive analysis, regression analysis, and BCA. Since the generic methodology is associated with various data, it is necessary to take into account the following data issues. Concerning the descriptive analysis and regression analysis, these methods require several performance measures associated with a particular asset. To conduct an *ex post facto* evaluation using ‘before and after’ data (i.e., time series data), the data need to include the performance measures used in the descriptive analysis and regression analysis. To conduct an *ex post facto* evaluation and *ex ante* evaluation using ‘with and without’ data, we need to predict future performances based on past or current performance with respect to the performance measures used in the analyses. To obtain the predicted performance measures, simulations based on various models (e.g., a deterioration model, speed model, and travel forecast model in HERS-ST) are required, while taking into account data related to infrastructure, traffic, and treatments and consequences. Hence, the *ex ante* evaluation needs additional data to simulate predicted performance as well as performance measures used in the descriptive analysis and regression analysis. The third analysis method, BCA, estimates agency, user, and external benefits. Hence, in both the *ex post facto* and *ex ante* evaluations, BCA requires data related to cost valuation.

This case study based on the *ex ante* evaluation addressed the positive results in the benefit quantification and the investment justification. In case of using the *ex post facto* evaluation, a result may not show benefits because of external influences (e.g., economy, environment, etc.) rather than HERS-ST implementation and the degree of conformity of an agency’s business to the M&R program recommended by HERS-ST.

The outcomes of this case study showed the HERS-ST’s ability to predict future pavement conditions, quantify detailed benefits based on elaborate functions derived from numerous past studies, and possibly justify investment in HERS-ST implementation compared to the costs for implementation. This implies that AMS which posses the required various data and simulation models to estimate assets conditions and benefits can analyze their benefits and investment using the generic methodology. Since collecting required data and developing simulation models are time consuming and complex tasks, the use of AMS to simulate predicted conditions and quantify benefits is recommended. Needless to say, it is important to determine appropriate simulation and valuation methods while focusing on specific assets. Also, in the case of analyzing different elements of asset management, such as pavement and bridge, at one time, it is necessary to have common performance measures in the descriptive analysis, the regression analysis, and the BCA.

7. Conclusions

A generic methodology for quantifying the benefits of AMS implementation and justifying investment in AMS implementation is presented in this paper. The generic methodology involves three analysis methods: descriptive analysis, regression analysis, and BCA. These methods rely on two evaluations: an ex post facto evaluation and an ex ante evaluation depending on the implementation of AMS and the availability of time series data. The case study analyzed the benefits of HERS-ST by focusing on pavement used an ex ante evaluation. The results showed the applicability of the generic methodology to quantify the benefits of HERS-ST implementation with respect to the 3Es. Also, the results identified the improvements in pavement conditions and the benefits of HERS-ST implementation consisting of agency, user, and external benefits. The case study suggested that HERS-ST implementation contributes to an improvement in agencies' performance and costs for M&R, and that the benefits derived from HERS-ST implementation will exceed costs for implementation and operation. Although the generic methodology is applied to HERS-ST only, the approach is rational and grounded in widely accepted practices for any AMS evaluation. The methodology and case study underscored some of the data challenges as data is not necessarily modeled or collected specifically for this type of analysis. The use of the generic methodology may reinforce the implementation and development of AMS through the articulation of benefits and justification of investment in transportation agencies.

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PART I: INTRODUCTION TO ASSET MANAGEMENT

Part I of this report presents the research problem addressed and the research goals and objectives. This section begins by raising the problems to be addressed and presenting the background and context for this research. The next chapter introduces the goals and objectives, approach, scope, and includes an outline of the remainder of the report.

Chapter 1. The Problem

Transportation agencies have identified asset management (AM) as a concept to support cost effective maintenance and rehabilitation decisions related to physical assets. Asset Management Systems (AMS) and tools are required to implement these AM concepts.

For transportation agencies, it is expected that AM improves agencies' performance in terms of the performance of their assets while it reduces agencies' cost for maintenance and rehabilitation (M&R). In a worst case scenario without asset management, M&R costs would continue to increase over time because of infrastructure deterioration caused by increases in the vehicle miles of travel, the increase in heavy trucks, aging infrastructure, and inappropriate M&R strategies. At the same time, the performance would degrade because M&R cannot catch up with the pace of deterioration of infrastructure due to the aforementioned reasons and an agency cannot afford to invest in the additional M&R needed due to budget constraints. Ultimately, the degradation in performance will translate to increased user costs. After implementing an AMS, appropriate M&R identified using the decision support tools in the AMS may improve performance and reduce costs simultaneously. Also, it is noted that there would be a reduction in user and external costs because appropriately maintained roads provide a better driving environment for users, thus reducing operational costs, crash costs, travel time costs, and environmental impacts.

Agencies are often hesitant to move forward in implementing AMS and tools, because it is difficult to document whether the benefits produced by AMS or tools exceed the costs for implementation and operation. Indeed six of seven research needs studies conducted since 2000 have identified "Measuring Benefits" as an important area of research to develop the base of support for asset management (Switzer and McNeil, 2004).

Understanding the relationship between the improvement of agencies' performance and costs for M&R is challenging. A new method is required to measure the benefits of implementing AMS and to demonstrate whether the benefits exceed the AMS implementation and operation costs. The method must be generic and adapt to different AMS and tools and applied to a variety of agencies with different resources.

The goal of the research is to develop a generic methodology for measuring the benefits derived from implementing an AMS. Benefits are defined as improvements in the transportation agency's business performance as well as improvements in their transportation system's performance as perceived by the users. These improvements are derived from the decision support provided by the AMS. An agency's business performance represents their M&R program while users' performance represents the driving environment. In this research, we will focus on pavement management because it is a primary business process and accounts for up to 60 % of the value of the total assets in a typical agency in the US.

This report documents research conducted to quantify the benefits of using AMS. The report begins by addressing the motivation for this research and presenting the problem statement that explains the reasons why asset management is the focus of this research. This chapter also provides the background information on the problem of asset management. In addition, the chapter states the goal and objectives of the research, overviews the approach used in the research, defines the scope, and finally presents contributions of the research.

1.1. Motivation

Transportation agencies aim to improve their asset performance while reducing their costs for maintenance and rehabilitation (M&R). Assuming, in a worst case scenario, M&R costs would continue to increase over time because of infrastructure deterioration caused by increases in the vehicle miles traveled (VMT), the increase in heavy trucks, aging infrastructure, and inappropriate M&R strategies. At the same time, the performance would degrade because M&R cannot catch up with the pace of deterioration of infrastructure due to the reasons aforementioned and an agency cannot afford to invest in the additional M&R needed due to budget constraints. As the infrastructure continues to deteriorate, resources for M&R and improvement would be constrained. As budgets are dependent on motor fuel taxes, they would not expand due to the resistance of politicians to increase taxes. Also, the Highway Trust Fund may need to provide more funding to offset the deficit. Since the degradation in asset performance will increase agency and user costs, agencies need cost-effective tools to improve asset performance.

In the U.S., most states have been developing Asset Management Systems (AMS) for specific types of infrastructure assets since the 1970's as an application of cost-effective tools to support M&R decisions. The importance of AMS has been reinforced by the Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991[1], the Governmental Accounting Standards Board (GASB) 34 guidelines[2] for asset reporting, and the continued degradation of physical assets in the U.S. Currently, AMS have become essential tools for transportation agencies to maintain, upgrade, and operate assets.

1.2. Problem Statement

Asset management is defined as a systematic process of maintaining, upgrading, and operating physical assets cost-effectively using an inventory of assets, a method of assessing current condition or performance, a process for determining needs, tools to evaluate and select appropriate strategies to address the needs, and methods to evaluate the effectiveness of each strategy (U.S. DOT et al., 1998).

Asset management systems (AMS) are tools to support the systematic process of maintaining, upgrading, and operating physical assets cost-effectively. Such systems include asset inventory, condition assessment and performance modeling, alternative selection and evaluation of maintenance and rehabilitation, methods for evaluating the effectiveness of each strategy, project implementation, and performance monitoring. AMS provide a holistic approach to strategic decision-making, which combines different management elements such as pavement management systems (PMS) and bridge management systems (BMS), based on a consistent evaluation manner, allowing agencies to trade off investment across the different elements. Also, AMS help agencies to understand the implications of different investment options (Cambridge Systematics, 2005). The benefits from asset management include more clearly defined objectives, more consistent approaches to prioritization, more transparency in decision-making,

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[1] The ISTEA, signed into law by President Bush in December 1991, aimed to create jobs, reduce congestion, rebuild infrastructure, help maintain mobility, help State and local governments address environmental issues, and ensure America's ability to compete in the global marketplace of the 21st Century (BTS, 2006).

[2] The GASB 34 was promulgated by GASB, a private, nonprofit organization, on June 15, 1999. Statement 34 calls for state, local, and municipal governments to calculate the original cost of infrastructure constructed or improved during the 20-year period prior to the Statement's issuance date in their annual financial reports (U.S. DOT and FHWA, 2000).

more efficient and effective uses of funding, more realistic stakeholder expectations concerning asset performance, improved understanding of trade-offs, better information to support investment decisions, and increased benefits to system users (U.S. DOT and FHWA, 1996; Austroads, 2002).

After a transportation agency implements AMS, appropriate M&R, identified using the decision-support tools, including condition prediction models and economic analysis tools in the AMS, may improve asset performance and reduce M&R costs simultaneously. Also, it is noted that there would be a reduction in user and external (non-user) costs because appropriately maintained roads provide a better driving environment for users, thus reducing operating costs, crash costs, travel time costs, and environmental impacts.

Yet, there are several barriers to implementing AMS in agencies. The 2004 Transportation Research Board (TRB) Asset Management Peer Exchange Meeting identified six barriers (Hendren, 2005):

1) Lack of integration using more sophisticated analytic tools to evaluate and prioritize M&R projects,
2) Database issues such as existing legacy system and costs for data collection,
3) Lack of adequate communication tools and methods for different audiences,
4) Jurisdictional issues such as lack of coordinated and consistent asset management approaches used by different agencies,
5) Institutional issues such as lack of coordinated and consistent asset management implementation, and
6) Implementation and development costs.

These barriers can prevent agencies from successful AMS implementation, which is defined as continual use of AMS from implementation to updating, reflection of the results of AMS (e.g., work order) in asset management, achievement of outcomes resulting from AMS corresponding to performance goals defined by agencies, and production of larger benefits (e.g., reduction of agency and user costs) than costs for AMS implementation and operation (Hopkins, 2001; Mizusawa and McNeil, 2005a).

Cost is an especially critical issue and barrier. Without showing that benefits of AMS implementation exceed costs for AMS implementation and operation, implementation will not occur. In particular, upper-level managers are interested in benefits that can be translated into monetary values (Smadi, 2004), because they need to justify their investment in AMS. Also, agencies that have already implemented AMS may require justification of past and continued investment in AMS.

Therefore, it is important to identify: Where do barriers exist?; What kinds of resources should be applied and where should these needed resources be applied in AMS implementation process?; Who are the important stakeholders to deal with the barriers and needs?; and How do stakeholders look at the barriers and needs? Also, methods to quantify benefits are required to justify AMS implementation using public resources. It is imperative to quantify the benefits of AMS implementation and demonstrate that the benefits exceed the implementation and operating costs, in order to disseminate and implement AMS in agencies.

1.3. Background

The U.S. transport system has been developing since the nineteenth century. In 1893, the Office of Road Inquiry started roadway research, construction of pre-interstate highways, and traffic surveys (FHWA, 1996; FHWA, 2003). After the era of major new highway construction, transportation issues changed from a focus on the expansion of the system network to increasing the efficiency of operating and managing the existing system. M&R costs continued to increase over time, performance degraded and user costs increased. Hence, transportation agencies such as state Department of Transportations (DOTs) implemented pavement management systems, one element of AMS. For example, Caltrans started collecting road performance information and using a PMS in 1977 (Lea and Harvey, 2004).

The ISTEA, enacted in 1991, provided encouragement for states to develop AMS for specific types of assets. ISTEA initially required states to have six AMS (Table 3) that cover all Federal-aid infrastructures by 1996, in order to optimize available funds used to preserve the national transportation infrastructure (Amekudzi and Attoh-Okine, 1996). The passage of the ISTEA enhanced and encouraged the development of AMS applications. Although the ISTEA management system requirement was rescinded in 1995, the National Highway System Designation Act of 1995 encouraged continued development and implementation of the ISTEA's management system (Institute of Transportation Engineers, 1999; McNeil et al., 1999; McNeil et al., 2000). Furthermore, ISTEA required agencies to introduce a long-range plan in their transportation planning (FHWA, 2002; Gayle, 1999). Agencies are using a systematic strategic planning approach to address future goals, objectives, and recommendations consisting of both capital investment and operation programs for the transportation system. In order to achieve these goals, management systems, which are a vehicle for showing assets' performances, are widely used (Mizusawa and McNeil, 2005b).

Some states instituted a strong driver, legislation, which requires agencies to utilize AMS and conduct business efficiently. For example, the state of Michigan passed Act 499 of the Public Acts of 2002 which established the Transportation Asset Management Council to advise the State Transportation Commission on a statewide asset management strategy for maintaining, preserving, and improving Michigan's federal-aid eligible roads and bridges, and the processes and necessary tools needed to implement the strategy (Michigan DOT, 2003). Also, the state of Vermont passed Sections 25 and 25 of Act No. 64 in 2001. They require the state agency to submit an asset management plan (i.e., list of assets and those condition, deterioration rates, annual funds necessary to fund M&R at the recommended performance level, M&R activities, and comparative cost differential between maintaining the infrastructure, utilizing a preventive maintenance program and deferring those maintenance costs) to the House and Senate Committees on Transportation (VTrans, 2002).

There is another driver: outsourcing by incorporating performance-based contracts[3] in road management. This strategy has been initiated in several states such as the District Columbia (FHWA, 2000a) to execute more cost-effective maintenance. Outsourcing, which requires both

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[3] The performance-based management contract type focuses on outcomes (i.e., the effects on society of outputs from governmental entities) of transportation project rather than process from inputs such as material and labor force to outputs such as bridge and pavement (FHWA, 2000b). Agencies do not specify any method or material requirements but specify performance measures that contractors are required to meet when delivering M&R goods and services (World Bank, 2005).

agencies and contractors to profile asset conditions and to utilize information and decision-support systems, has encouraged agencies to utilize AMS.

Table 3. ASSET MANAGEMENT SYSTEMS REQUIRED BY ISTEA

ISTEA – Asset Management Systems
Pavement Management System
Bridge Management System
Highway Safety Management System
Traffic Congestion Management System
Public Transportation Facilities and Equipment Management System
Intermodal Facilities and Systems Management System

Moreover, the GASB 34 guidelines have been another driver encouraging PMS implementation. In 1999, the GASB 34 guidelines were instituted requiring state and local agencies to report the book value of physical assets. These guidelines also motivated agencies to develop and implement integrated AMS so that they can evaluate their assets' value and include their value on financial reports using an inventory system and investment analysis in AMS and private sector business principles (Cowe Falls and Tighe, 2004).

Over the last decade, the Office of Asset Management of the Federal Highway Administration (FHWA) and arms of professional organizations, the American Association of State Highway and Transportation Officials (AASHTO) and the Transportation Research Board (TRB), have been studying best practices and disseminating to agencies asset management concepts extracted from their studies (McNeil et al., 2000; Switzer and McNeil, 2004). Politicians, engineers, planners, and academicians have identified AMS as tools to support cost effective maintenance, upgrading, and operations decisions related to physical transportation assets.

For agencies, it is expected that AMS will improve their performance in terms of the performance of their assets while it reduces agencies' cost over the life cycle of the assets. In a worst case scenario without asset management, M&R costs would continue to increase over time because of infrastructure deterioration caused by increases in the vehicle miles of travel, the increase in heavy trucks, aging infrastructure, and inappropriate M&R strategies. After implementing an AMS, appropriate M&R identified using the decision support tools in the AMS may improve performance and reduce costs simultaneously. Also, it is noted that there would be a reduction in user and external costs because appropriately maintained roads provide a better driving environment for users, thus reducing operating costs, crash costs, travel time costs, and environmental impacts. This scenario is shown in Figure 6. In reality, the decision making process is actually more complex as agencies tradeoff investments among capital and M&R projects, different facilities, and different time periods. M&R costs may actually increase for an agency using an AMS, but life cycle costs will be reduced (U.S. DOT and FHWA, 2002a).

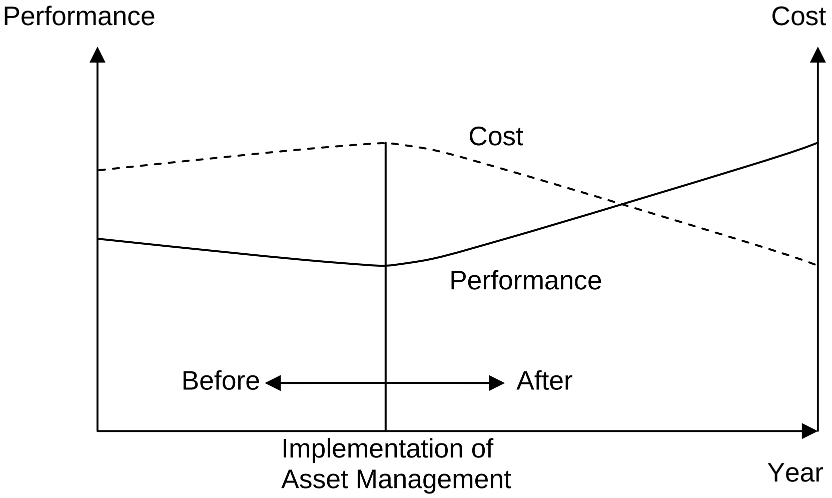

Figure 6. Conceptual relationship between performance and cost before and after implementing AMS

Another way to look at the issue is in terms of the changes in various variables over time. Figure 7 depicts the relationships among problems and solutions in urban transportation. The problems described above: the increase of VMT causing congestion and environmental problems, and the burden of maintaining the existing transport system stock due to the increase of heavy trucks, aging infrastructure and rapid traffic growth, are depicted. Focusing on roads, just one part of the transport systems, there are two main methods to deal with the problems. One is to apply policies to influence the demand side as shown in the graph of demand over time. For example, Singapore implemented the Restricted Zone Area Licensing Scheme (ALS) in 1975 to restrict automobile access to the central business district during business hours on weekdays and Saturdays. Also, Hong Kong introduced a series of fiscal measures to restrain automobile ownership such as a First Registration Tax (FRT) and tripling the annual vehicle license fee in 1974 (Cameron et al., 2004). These traffic restraint policies discourage automobile ownership and discourage automobile owners from using their automobiles, thus reducing congestion and environmental impacts, and maintenance costs. However, the policies could exacerbate a budget problem if the budget heavily relies on taxes imposed on both gasoline and automobiles. This may cause a difficulty in retaining adequate maintenance costs.

The other method is, on the supply side, as shown in the graph of supply over time, to increase the efficiency of operating and managing the roads using applications such as rational urban planning, implementations of Intelligent Transportation Systems (ITS) strategies, and AMS. For example, in Europe, urban planning oriented to rail transit, rather than roads, contributes to increasing the efficiency of the transport system (Cameron et al., 2004). In the U.S., electronic toll collection (ETC) systems alleviate congestion at toll gates (U.S.DOT, 2004). Those methods improve traffic flow and reduce congestion and environmental impacts as shown in the graph of congestion or pollution over time. However, there is a debate as to whether the increase in supply aggravates environmental impacts due to induced additional traffic (Stathopoulos and Noland, 2003).

In addition to the two applications aforementioned, AMS contribute to the efficiency of operating and managing the roads by maintaining, upgrading, and operating them as shown in the graph of maintenance costs over time. Specifically, AMS provide answers to questions such as (Flintsch et al., 2004):

- What are the most cost-effective general M&R strategies?
- Where (or what) M&R treatments are needed?
- When is the best time (condition) to program a treatment?

AMS differ from both rational urban planning and ITS implementation because AMS do not improve traffic flow on roads but focus on maintaining and supporting existing services – the supply side – using appropriate M&R (e.g., routine and periodical maintenance, resurfacing, and reconstruction) in order to provide a better driving environment. Yet, comparing roads that are appropriately maintained to those that are deteriorated, drivers prefer a smooth surface maintained through the decision support provided by AMS[4]. Also, AMS give full play to the contribution of both sound urban planning and innovative ITS. Hence, it can be said that AMS is one supply side method to increase the efficiency of operation and management of the roads. Furthermore, AMS may optimize limited budgets through cost-effective management, thus reducing maintenance costs. With the benefits of AMS, agencies can approach the goal of sustainable development without heavy dependence on the public purse, because their unavoidable burden of maintenance costs will be reduced and the resources can be utilized to decrease the deficit or invest in other developments, while they still retain a desirable level of service of infrastructure.

In summary, this chapter introduced the concepts of asset management, described the value of asset management, and identified barriers to asset management system implementation as well as the need to address these barriers and quantify the benefits of asset management system implementation.

The following chapter lays out the goals and objectives of this research, provides an overview of the research approach, and outlines the remainder of the report.

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[4] HERS-ST (Highway Economic Requirements System-State Version), one Pavement Management System (PMS), provides a widening option for road segments where there is no enough capacity to hold current traffic volume. Given this option, it is expected that traffic capacity will increase at the segments and improve traffic flow. Also, HDM-4 (Highway Development and Management Tool), a widely-used PMS in developing countries, provides upgrading option from unpaved surface to paved surface. This option significantly improves vehicle speed (e.g., unpaved very poor condition: 28km/hr; paved very good condition: 85km/hr) and thus traffic flow (Archondo-Callao, 2004). Although it cannot say that AMS per se improve traffic flow, those outputs do.

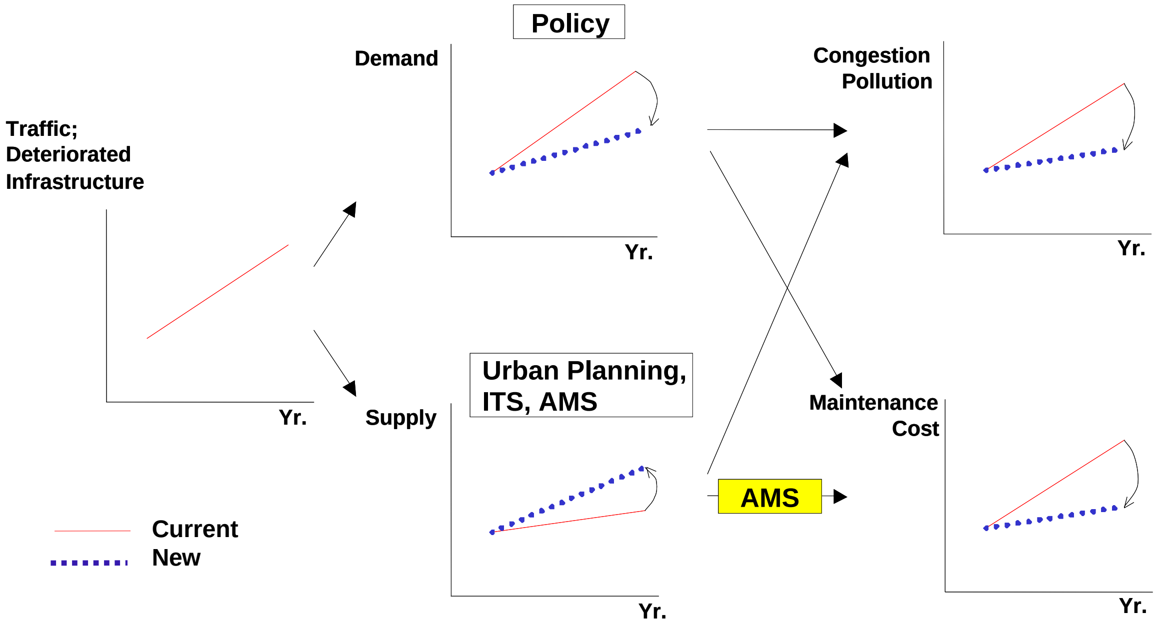

Figure 7. Relationships among urban transportation problems and solutions

Chapter 2. THE RESEARCH

This chapter introduces the goals and objectives of the research, overviews the approach used in the research, defines the scope, and presents an outline of the report.

2.1. Research Goals and Objectives

The primary goal of the proposed research is to develop a generic methodology for quantifying benefits derived from implementation of AMS. Benefits are defined as improvements in the transportation agency's business performance as well as improvements in the transportation system's performance as perceived by users. These improvements are derived from the decision support provided by AMS. An agency's business performance is represented by the M&R program while users' performance is represented by the driving environment.

The primary goal has three objectives in developing a generic methodology for quantifying AMS benefits as follows:

- Analyze whether AMS implementation contributes to the improvement of agencies' performance and costs for M&R,
- Demonstrate that benefits derived from AMS implementation exceed costs for implementation and operation, and
- Support the use of AMS and asset management concepts by suggesting solutions for breaking through barriers existing in the implementation process and justifying investment in AMS and tools.

These objectives are accomplished in response to the following research questions:

- Does an agency increase productivity[5] and decrease costs with AMS?
- Does the public realize user and external cost reductions due to AMS implementation?
- Do benefits of implementing AMS exceed implementation and operating costs?

The process for achieving the objectives above addresses the secondary objectives as follows:

- Identify benefits and costs of AMS implementation from different stakeholders' perspectives,
- Compare methodologies for quantifying benefits,
- Propose a generic methodology for quantifying AMS benefits, and
- Evaluate the generic methodology using case studies.

The secondary goal is to understand AMS implementation for addressing strategic directions for successful AMS implementation as final research outcomes, including the generic methodology. The secondary goal has two objectives as follows:

- Understand AMS implementation processes not only from the U.S. but also from international experiences, and
- Identify barriers and needs in AMS implementation processes.

2.2. Approach

Although participants from transportation agencies in the TRB Peer Exchange Meeting addressed the barriers and next steps to implementing AMS (Hendren, 2005), those were derived

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[5] Productivity is the rate at which improvements in the agency's business performance and transportation system's performance are produced.

from only a limited number of participants and discourse. Hence, this research analyzes the AMS implementation process to provide a more detailed comprehensive context for the barriers and needs. Then, the result of the comprehensive analysis, which provides directions for a successful implementation process taking into account the barriers and needs, is translated into an implementation strategy. At the same time, a generic methodology for quantifying AMS benefits is developed as one solution corresponding to the existing barriers in AMS implementation. The generic methodology is incorporated into the strategic directions as the final outcome of this research.

The implementation strategy and the generic methodology for quantifying AMS benefits are developed using the following approach:

- **Identify barriers and needs to deal with the barriers:** The research identifies the kinds of barriers that exist and the needs of agencies required to support effective AMS implementation. Domestic and international experiences are used to identify ideas for breaking through the barriers.
- **Discuss how the needs should be applied:** Based on the barriers and needs obtained from the previous task, this research addresses: Where do barriers exist?; What kinds of resources should be applied and where should the needed resource be applied in AMS implementation process?; Who are the important stakeholders to deal with the barriers and needs?; How do stakeholders look at the barriers and needs?.
- **Identify benefits and costs of implementing AMS:** Given the introductory nature of the previous tasks, this research task gets to the core part, methods to quantify benefits of AMS implementation to deal with the critical barrier, costs. In order to demonstrate that benefits exceed the implementation and operating costs later, the research identifies benefits derived from AMS implementation and costs for implementation.
- **Identify methods to quantify the benefits:** This research reviews the methods of quantifying benefits conducted by researchers or agencies not only in asset management evaluation studies but also in other infrastructure evaluation studies. Also, it analyzes those methods to determine whether they can be applied to quantifying benefits of AMS implementation and addresses problems identified in the analysis.
- **Build a framework to quantify the benefits:** By taking into account the strengths and weaknesses found in the previous task, this research builds a framework for a generic methodology to quantify the benefits.
- **Propose a generic methodology:** After developing the framework, the research performs case studies using the framework to evaluate their performance in terms of whether they can quantify the benefits of AMS implementation. Based on the findings, it proposes a generic methodology that agencies can use to estimate the benefits of AMS implementation.
- **Discuss AMS implementation:** The research then discusses whether the implementation of AMS is beneficial to improving agencies’ business performance, users’ performance, and environmental impacts.
- **Address strategic directions for AMS implementation:** Throughout the tasks above, the research addresses strategic directions for successful AMS implementation, including how the needs should be applied to deal with the barriers and the generic methodology for quantifying the benefits of AMS implementation, in order to disseminate AMS and asset management concepts to agencies.

2.3. Scope

The scope of this research is to develop strategic implementation directions addressing how AMS should be implemented and evaluate their cost-effectiveness using a generic methodology. The successful implementation factors and processes are developed based on the literature review and interviews. The methods to quantify the benefits of AMS implementation are derived from literature review. After that, a generic methodology is developed based on the result of case studies. The research focuses on pavement management as one element of asset management since pavement management is a significant activity and pavements account for up to 60 percent of the total assets in a typical agency in the U.S. (Flintsch et al., 2004). While the cultural change required to implement asset management in an organization is equally important, such change is beyond the scope of this project.

2.4. Outline of the Report

This report documents the implementation strategy and generic methodology for quantifying benefits of AMS in the following chapters as follows:

PART II includes Chapters 3 to 5. This section focuses on evaluating the benefits of asset management to achieve the primary research goal.

Chapter 3 documents a framework to quantify the benefits of AMS implementation and justify investment in AMS implementation, which is developed by literature review. The framework focuses on pavement management, that is, one element of asset management. Also, this chapter addresses data issues for utilizing the framework.

Chapter 4 documents case studies that evaluate the implementation of two asset management systems using the framework identified in Chapter 3. Each case study presents a background, analysis methods, analysis results, lessons learned, and summary.

Chapter 5 summarizes the framework as a generic methodology to quantify the benefits of AMS implementation and justify investment in AMS implementation. In addition, this chapter discusses whether the implementation of AMS is beneficial to agency, user, and externality based on the results obtained from Chapter 4.

Finally, PART III concludes this research with summary, contributions, recommendation, and future research. Cited references are also listed at the end of this part.

Appendices document supporting materials. Appendix A reviews a theoretical approach to quantifying the benefits and costs of asset management. Appendix B reviews six papers that illustrate the application of different methods to quantify and analyze the benefits of introducing new systems including pavement management systems, transit systems and intelligent transportation systems (ITS). Appendix C documents the data from the Vermont Transportation Agency (VTrans) used for the case study presented in Chapter 4. Appendix D reports the results of the case study for VTrans in terms of the percent length by pavement condition. Finally, Appendix E describe the performance measures used in the Highway Economics Requirements Systems – State Version (HERS-ST) that serves as the second case study in Chapter 4.

2.5. Contribution of the Research

Transportation agencies are facing the problem of deteriorated transport system and budget constraints. Since the transportation issues changed from a focus on the expansion of the system network to increasing the efficiency of operating and managing the existing system, AMS are required to deal with these problems proactively. Because few researchers have (or little research has) investigated methods for quantifying the benefits of AMS and collected information on successful implementation systematically, this research will significantly contribute to the reinforcement of asset management principles. Providing directions for successful AMS implementation and generic methodology for quantifying benefits of AMS will encourage agencies to disseminate, implement and develop AMS and asset management concepts. Furthermore, agencies may be able to alleviate or solve the urban transportation problems addressed in **Figure 7**.

The products of this research are documents of strategic directions for AMS successful implementation including analysis of barriers and needs in AMS implementation, summary of methods of quantifying benefits of AMS implementation, and results of developed generic methodology for quantifying benefits and its performance derived from case studies.

PART II: QUANTIFYING THE BENEFITS OF ASSET MANAGEMENT

Part II of this report focuses on evaluating the benefits of asset management to achieve the primary research goal. This section begins with a framework to quantify the benefits of AMS implementation, emphasizing pavement management. The next chapter documents case studies to evaluate AMS implementation using the framework to quantify the benefits of the implementation. The final chapter summarizes a generic methodology in terms of its usage and applicability, and discusses the benefits of AMS implementation.

Chapter 3. METHODOLOGY

This chapter documents a framework to quantify the benefits of implementing AMS, with particular emphasis on pavement management. The framework draws on past research reviewed in APPENDIX A and APPENDIX B. Also, this chapter addresses data issues for utilizing the framework.

3.1. Framework

The primary goal of the research is to develop a generic methodology for quantifying the benefits of AMS implementation. Given the quantified benefits of AMS implementation, we can achieve the research objectives: 1) analyze whether AMS implementation contributes to the improvement of agencies' performance and costs for M&R, and 2) demonstrate that benefits derived from AMS implementation exceed costs for implementation and operation. In order to build a generic methodology for quantifying the benefits, we will focus on PMS as a preliminary experiment.

This framework will not evaluate qualitative benefits such as improved communication and customer satisfaction identified in APPENDIX A. However, the framework is intended to be applicable to the inclusion of qualitative benefits through future research to obtain more complete results if the qualitative benefits are evaluated using performance measures. Based on the following three research questions, the framework for a generic methodology is developed to address the following questions:

1. Does an agency increase productivity and decrease costs with AMS?
2. Does the public realize user and external cost reductions due to AMS implementation?
3. Do the benefits of implementing AMS exceed implementation and operating costs?

The remainder of this section has five parts: criteria for evaluation, evaluation design, benefit quantification, investment justification, and relationships. The first section describes the criteria for evaluation. The second section, evaluation design, addresses how to capture the benefits of PMS implementation depending on data availability. The third section, benefit quantification, responds to the first and second questions above using three analysis methods to quantify the benefits of PMS implementation. The fourth section defines one analysis method to justify investment in PMS implementation using quantified benefits of PMS implementation, which responds to the third question. The last section shows the relationships between the analysis methods in the framework.

Criteria for Evaluation: Efficacy, Effectiveness and Efficiency (3Es)

Drawing on work in Soft Systems Methodology (Checkland 1999), we distinguish among different approaches to quantifying the benefits of PMS implementation and justifying investment in PMS implementation, with respect to the 3Es, efficacy, effectiveness, and efficiency, defined as follows (Mizusawa 2007):

- Efficacy: shows whether PMS work or not. The efficacy can be recognized as the difference in performance between 'before' and 'after,' or between 'with' and 'without,' using descriptive analysis and regression analysis. Also, the BCA quantifies the efficacy using the net benefits (i.e., benefits including reductions in agency, user, and external costs minus M&R costs), and the ratio of benefits to costs for M&R treatments.

- Effectiveness: identifies the degree to which PMS achieve the agency's asset management goals. Effectiveness is determined by the difference, but needs to be addressed in term of degree. If the degree is addressed, an agency can observe to what extent asset conditions meet their asset management goals compared to the case of 'before' or 'without.' The results of descriptive analysis, regression analysis, and BCA can articulate the effectiveness.
- Efficiency: identifies optimal use of resources using the ratio of output or outcome to input of PMS. Efficiency can be quantified by the comparison of the ratios of benefits to costs for M&R treatments between 'before' and 'after,' or between 'with' and 'without.' If the costs for M&R before and after, or with and without PMS implementation are available, the different ratios of performance (e.g., pavement condition) to the costs between 'before' and 'after,' or between 'with' and 'without,' assess the efficiency of PMS implementation. All three analysis methods are capable of assessing the efficiency.

Evaluation Design

There are two types of evaluation design: an *ex post facto* and *ex ante*. An *ex post facto* or retrospective evaluation is applied to agencies that have already implemented PMS. On the other hand, an *ex ante* or prospective evaluation is applied to agencies that are going to implement PMS. Since we need to quantify the benefits of PMS implementation that manage a whole network, we focus on performances in network level hereafter.

Figure 8 shows the concepts of an *ex post facto* evaluation, which includes two types: a comparison of actual performances, such as pavement condition, before and after PMS implementation (left hand side); and a comparison between predicted performance if PMS had not been implemented and actual performance after PMS implementation (right hand side). Similar to the analyses of Hudson et al. (2001) and Cowe Falls and Tighe (2004), the first type observes trends in pavement condition using time series data to make a comparison between before and after PMS implementation. The second type needs time series data of the actual pavement condition both before and after PMS implementation as well. The actual pavement condition before PMS implementation is used to predict pavement condition without PMS after the year of PMS implementation based on a strategy before PMS implementation (e.g., a worst first) and to compare this to the actual pavement condition with PMS after PMS implementation. This type includes the analysis by Smadi (2004). Since the actual pavement conditions after PMS implementation are outputs of pavement management based on a PMS optimization strategy, it is expected that the actual pavement conditions after PMS implementation are better than the actual pavement conditions before PMS implementation and the predicted pavement conditions without PMS after the year of PMS implementation. The improvement in the pavement conditions 'before' and 'after' PMS implementation (left hand side) and 'with' and 'without' PMS implementation (right hand side) in the comparisons represents the benefits of PMS implementation in terms of asset performance.

Since the time series data required for *ex post facto* evaluation are rarely available in transportation agencies, we need an alternative evaluation method. That is the *ex ante* evaluation depicted in Figure 9. Using current performance data, two different future performances are simulated based on strategies: 'without PMS' (e.g., a worst first strategy) and 'with PMS' (i.e., a PMS optimization strategy). The predicted condition without PMS can simulate the past actual pavement condition before PMS implementation, while the predicted condition with PMS can simulate the past actual condition after PMS implementation. In addition, since future pavement conditions can be simulated based on the strategies, the *ex ante* evaluation can analyze the benefits of PMS implementation even though an agency had not implemented PMS. Although the predicted conditions do not represent real pavement condition, they can show the difference in pavement condition between 'with PMS' and 'without PMS', that is, the benefits of PMS implementation. As demonstrated, the *ex ante* evaluation is similar to the *ex post facto* evaluation (right hand side in Figure 8) that compares predicted conditions without PMS implementation to actual conditions after PMS implementation. This is a quasi evaluation design to recognize benefits in pavement conditions between 'with PMS' and 'without PMS.'

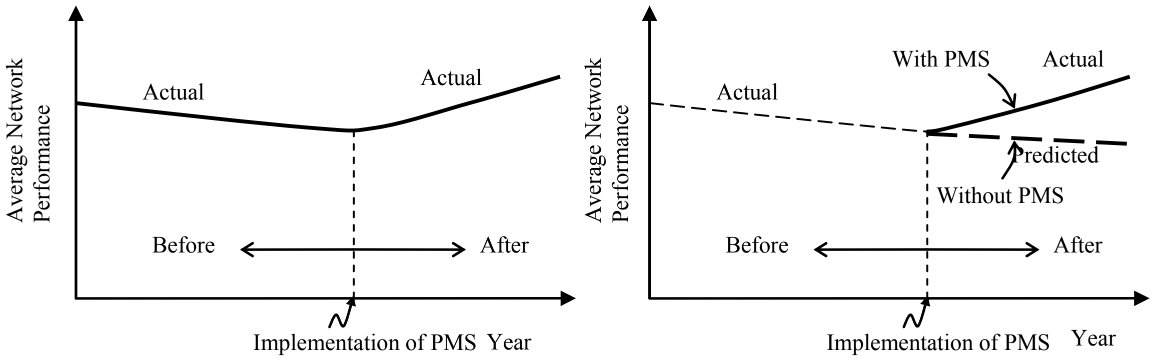
Ex post facto

Figure 8. Concepts of ex post facto Evaluation

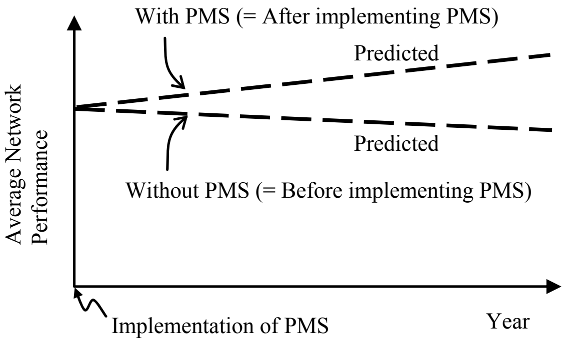
Ex ante

Figure 9. Concepts of ex ante Evaluation

The PMS recommends more frequent and preventive treatments and minor rehabilitations while taking into account future pavement conditions. These are relatively small-scale works compared to the worst first strategy's reactive treatments that are less frequent and more significant than many PMS treatments. Thus, the PMS treatments are less expensive than the worst first strategy's treatments over a long period, to keep a minimum acceptable pavement in a network level. Furthermore, the budget saved by the treatments can be used for further treatments. Hence, it is expected that the pavement conditions with PMS are improving more than that without PMS as time goes by because of the efficiency of treatments.

The framework has three analysis methods: the first is a descriptive analysis based on common performance measures that capture users in terms of traffic volume and conditions; the second is a regression analysis intended to quantify the contribution of AMS to improved performance; and the third is a benefit-cost analysis. Those methods can be used together or independently.

Benefit Quantification

For quantifying the benefits of PMS implementation, we need to articulate the efficacy, effectiveness, and efficiency (3Es) of PMS implementation. The following methods can be used to show the 3Es.

Descriptive Analysis Using Before and After (With and Without) Data

At first, it is important to recognize that trends of an agency's performance (e.g., pavement condition, budget, and expenditure) and exogenous effects (e.g., economy, traffic volume, and environment) in addition to an agency's profile in terms of asset, organizational structure, legislature, PMS, and so on. The descriptive analysis can analyze the first research question by showing various trends using performance measures between before and after PMS implementation or with and without PMS implementation. The trends can be observed by either the *ex post facto* evaluation or the *ex ante* evaluation. The descriptive analysis using before and after (with and without) data tries to identify whether and how much an agency's performance is improved from the condition before (or without) PMS implementation to that after (or with) PMS implementation. These articulate the efficacy and effectiveness of PMS implementation. Also, the comparison of ratios of outputs to inputs between before and after (with and without) can identify the efficiency, such as the ratios of improvements of pavement condition to costs for M&R treatments.

It is hypothesized that the performance measures after (without) PMS implementation are superior to those before (without) PMS implementation. The following performance measures related to pavement condition can be applicable to before and after analysis:

- Average pavement condition by year (Scale: 0-100): this measure captures an agency's performance because it focuses on pavement managed by an agency.

$$\text{Average Pavement Condition} = \frac{\sum_{i=1}^{n}(PCI_i \times Length_i)}{\sum_{i=1}^{n} Length_i} \qquad (7.1)$$

where:

PCI : Pavement condition index variable
Length : Length of road sections in mile
i : Road section number (i = 1, …, n)

- Traffic weighted average pavement condition by year (Scale: 0-100): This measure captures two perspectives: users' performance and an agency's performance, because it focuses on pavement in conjunction with traffic volume.

$$\text{Traffic Weighted Average Pavement Condition} = \frac{\sum_{i=1}^{n}(PCI_i \times AADT_i \times Length_i)}{\sum_{i=1}^{n}(AADT_i \times Length_i)} \quad (7.2)$$

where:

PCI : Pavement condition index variable
AADT : Annual average daily traffic
Length : Length of road sections in mile
i : Road section number (i = 1,…, n)

These measures can be plotted by year and differences between before and after conditions or with and without conditions illustrated visually. Summary statistics, for example, the average measurement value over a fixed period can also be examined.

In addition, effectiveness is used as one performance measure. This is commonly used in pavement management. The effectiveness is considered as an alternative of benefits because it "*is valuable in the relative comparison of alternatives and in carrying out priority programming*," even though there is "*no physical or economic meaning per se*" (Haas et al., 1994).

Figure 10 depicts a schematic illustration of effectiveness using the comparison between the pavement condition curve with PMS and without PMS in an *ex ante* evaluation. Effectiveness is the net area under the curve (i.e., the area under the curve with PMS minus the area under the curve without PMS) multiplied by traffic volume and length of road sections; that is:

$$\text{Effectiveness} = \sum_{i=1}^{n}\sum_{t=1}^{m}\left\{\left(PCI_{i,t}^{w/PMS} - PCI_{i,t}^{w/oPMS}\right) \times AADT_{i,t} \times Length_i\right\} \quad (7.3)$$

where:

PCI : Pavement condition index
AADT : Annual average daily traffic
Length : Length of road sections in mile
i : Road section number (i = 1,…, n)
t : Year (t = 1,…, m)

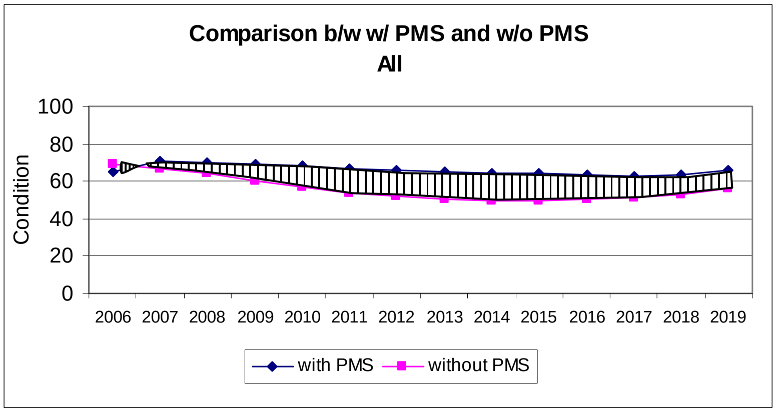

Figure 10. Schematic illustration of effectiveness

Effectiveness is displayed in units of pavement conditions index point-vehicle miles. As this is not an intuitive or real unit of measure, we assume the quantity is unit-less. The result of the effectiveness derived from the net area under the curve gives us an aggregate measure with which to assess the efficacy of PMS. If the result is positive, PMS improves pavement conditions.

There are two advantages in the before and after (with and without) analysis. First, performance measures can address qualitative benefits using surveys with scoring systems, although the surveys are cumbersome. Second, it is simple and can be tailored for any agencies based on available data. On the other hand, there are two disadvantages. One is that performance measures cannot reflect the complete benefits, as that requires multiple measures in the analysis. The other is that this analysis cannot control for changes when addressing benefits of PMS implementation. The comparison between before and after PMS implementation needs to be based on the same analysis condition consisting of variables such as traffic volume, budget, and network length when comparing the performance measures.

Regression Analysis

Using the network level performance measures developed for the descriptive analysis, regression analysis can be performed to address the weaknesses of the descriptive analysis using before and after (with and without) data, specifically, not being able to consider various changes simultaneously. This analysis is intended to articulate answers to the first research question by observing the degree of independent variables' influences on a dependent variable expressed by the coefficients.

There are three tasks in the analysis: 1) Find an appropriate dependent variable representing productivity. We can assume productivity is an increase of PCI, increase of pavement life, reduction of M&R costs, and so on. It is necessary to explore various measures and determine an appropriate one. 2) Identify independent variables which are statistically significant. For example, we can identify significant variables using t-values. 3) Determine a type of regression model. Among many types such as linear, polynomial, log linear, and so on, we should determine the best type by measure of fit (i.e., R-Square).

Examples of models are as follows:

Model 1: $\text{Average Pavement Condition}_t = f(X_t, \text{PMS}_t)$
Model 2: $\text{Traffic Weighted Average Pavement Condition}_t = f(X_t, \text{PMS}_t)$
where:
For t =1,…, T
Average Pavement Condition (APC) : Average pavement condition in year t
Traffic Weighted Average Pavement Condition (TWAPC) : Traffic weighted average pavement condition in year t
X_t : Vector of independent variables such as AADT, length, and M&R treatment costs in all road sections in year t
PMS_t : Use of PMS in year t (dummy variable: 1- yes; 0- no)

To build the models at the network level, time series data including pavement conditions and various measures, such as AADT, length, and M&R treatment costs, in all road sections are required. The coefficient for the dummy variable PMS indicates the impact of the use of PMS on the performance measures. This impact articulates the efficacy and effectiveness of PMS implementation. If we set the ratios of improvements of pavement condition to costs for M&R treatments in the dependent variable, for example, we may be able to show the efficiency of PMS implementation. Also, if the same costs for M&R treatments are used for before and after (with and without), the coefficient implies the efficiency of PMS implementation. Ordinary least squares (OLS) regression is used to build the models, as the average pavement condition can be assumed to be independently and identically distributed.

Benefit-Cost Analysis

BCA is employed to answer the first question, and also, where possible the second question, because BCA can estimate user and external costs. The following subsections describe the foundation for BCA including the principles, elements, and methods of BCA in light of the analysis of PMS implementation.

Principles

BCA is grounded in analysis principles that are designed to determine whether any of a set of mutually exclusive alternatives is economically worthwhile, and if so, which alternative is the most desirable in an economic sense (Hendrickson and Wohl, 1984.) One of the challenges for projects that provide services to the public, such as roads or transit, is that the benefits to the public of each project are unknown or very difficult to assess. Therefore, we assume that the project is worthwhile and the analysis focuses on selecting the most desirable alternative. Table 4 defines alternatives for which benefits and costs can be measured in relative terms.

Table 4. LIST OF ALTERNATIVES IN BENEFIT QUANTIFICATION

Alternative	Data	Description
Existing (or Status Quo) alternative	Benefits and Costs reported in relative values	Pavement management before (without) PMS implementation for existing highway system compared with do-nothing
New alternative	Benefits and Costs reported in relative values	Pavement management after (with) PMS implementation for existing highway system compared with do-nothing

BCA focuses on benefits and costs of alternatives for a project. Usually, each alternative addresses benefits produced by the project and costs incurred by the project. An important element of BCA is determining from which perspective to conduct the analysis. As highway agencies provide a service, the analysis must be conducted from a social welfare perspective, which recognizes the benefits to users. In the case of a water utility, customers pay directly for the service and the utility's perspective includes profit. User fees are a benefit to the utility. However from a social welfare perspective, user fees are a transfer payment. Sometimes they are considered to serve as a proxy for the benefit that the users receive from the service. However, in the case of PMS implementation on pavement management, the benefits produced by PMS implementation are difficult to quantify. Therefore, benefits of PMS implementation are most conveniently measured as incremental or relative benefits between a base case and cases when either a worst first strategy or PMS is implemented. A base case can be to do-nothing (i.e., not adopting pavement management or the existing alternative). The base case and the adoption of pavement management are assumed to be mutually exclusive.

There are two alternatives to illustrate two pavement management strategies, before (or without) PMS implementation and after (or with) PMS implementation. This comparison can articulate whether and how much PMS implementation improves benefits (i.e., efficacy and effectiveness) using benefits derived from pavement management compared to do-nothing and initial costs for M&R for each alternative. If differential benefits and initial costs between the alternatives are available, it is possible to identify the net benefits of pavement management before (or without) and after (or with) PMS implementation and analyze which pavement management is efficient, before (without) or after (with).

At first, we need to identify benefits and costs related to pavement management. As Cowe Falls and Tighe (2004) and Hudson et al. (2001) demonstrated, benefits and costs for before (without) and after (with) PMS implementation are required. Table 5 lists benefits and costs related to pavement management. There are three kinds of benefits: agency's benefits including reduction in the cost of M&R, savings in user costs, and reduction in environmental costs. Although a wide spectrum of benefits of AMS implementation was addressed in APPENDIX A, we use the benefits that can be monetized here.

After specifying alternatives and benefits and costs, benefits and costs need to be estimated to conduct BCA using the following elements and methods.

Table 5. BENEFITS AND COSTS IN BENEFIT QUANTIFICATION

Category		*Description*
Benefits	Agency	Reduction in the cost of M&R
	User	Savings in user costs, including travel time cost, vehicle operating cost, safety cost Incremental user surplus
	External (non-user)	Reduction in environmental costs, which are subjected to non-user.
Costs	Agency	Initial costs for M&R treatments

Estimation of Benefits and Costs

The year-by-year benefits and costs associated with the investment and usage (known as the cash flow) are estimated over the analysis period (Hendrickson and Wohl, 1984). To estimate the benefits and costs for each alternative, we define:

- $B_{x,t}$ = expected benefits from alternative x during year t
- $C_{x,t}$ = expected costs or outlays (whether capital or operating) for alternative x during year t

Also, two other pieces of information must be specified:

- The analysis period, n
- The discount rate, expressed in decimal form, i

Analysis Period

All alternatives must be analyzed for the same analysis period or planning horizon to take into account the benefits and costs related to a project. The length of analysis period depends on: 1) the expected life of the project, and 2) the period in which we can fairly reliably predict benefits and costs (Hendrickson and Wohl, 1984).

Discount Rate

Although the benefits and costs arise from different sources and are accrued or increased in different time periods throughout the analysis period, we need to consider them at the same time in BCA. Since the monetary value changes over the analysis period, we have to set not only the specific time when we analyze the benefits and costs, but also the values of the benefits and costs to a consistent (discounted) monetary value using an discount rate.

In order to determine the discount rate, we can refer to the rate of return on money markets or the rate for all projects being considered by a decision-making unit such as the Office of Management and Budget (OMB) and the Congressional Budget Office (Weimer and Vining, 2004).

Methods

To compare and prioritize alternatives, two BCA methods are commonly used (Hendrickson and Wohl, 1984). These are described below. Examples of the application of these methods including a discussion of the assumptions required can be found in Mizusawa (2007).

- Net Present Value (Net Present Worth) Method

The net present value method is one common method. The stream of benefits and costs are discounted to their present value or present worth (that is, to their value now) and then netted to determine the resultant net present value. For any alternative x, the net present value for the n year analysis period when the discount rate is i the $[NPV_{x,n}]_i$ is:

- $[NPV_{x,n}]_i = [TPVB_{x,n}]_i - [TPVC_{x,n}]_i$

$$= \sum_{t=0}^{n} \frac{B_{x,t}}{(1+i)^t} - \sum_{t=0}^{n} \frac{C_{x,t}}{(1+i)^t} = \sum_{t=0}^{n} \frac{B_{x,t} - C_{x,t}}{(1+i)^t} \qquad (7.4)$$

where:

[TPVBx,n]i : Total discounted benefits for an n-year period and discount rate i
[TPVCx,n]i : Total discounted costs for an n-year period and discount rate i

For prioritizing alternatives, the alternative that has the largest net present value should be chosen as the most appropriate alternative.

- Benefit-Cost Ratio Method

In addition, the benefit-cost ratio method is a well-known method similar to the net present value method. The differences from the net present value method are that extra computations are required for the benefit-cost ratio method and that proper interpretation of the ratios may be confusing in some cases. This method consists of the followings two steps:

- Step 0: Order alternatives in terms of increasing internal investment.
- Step 1: Determine whether any alternative is economically worthwhile.

$$[BCR_{x,n}]_i = \frac{[TPVB_{x,n}]_i}{[TPVC_{x,n}]_i} \geq 1.0 \qquad (7.5)$$

where:

[BCRx,n]i : Benefit-cost ratio for alternative x over an n-year analysis period for a discount rate i
[TPVBx,n]i : Total discounted benefits for an n-year period and discount rate i
[TPVCx,n]i : Total discounted costs for an n-year period and discount rate i

- If the ratio is at least as large as 1.0, the net present value is nonnegative.
- If the ratio for the lowest cost alternative is less than 1.0, then it will be rejected and the ratio will be computed for the next higher initial cost alternative.
- If all alternatives have a ratio less than 1.0, then all should be rejected.

- Step 2: Determine whether or not it is worthwhile to undertake an even higher-ordered alternative. (Pairwise comparison)

$$[IBCR_{x/x+1,n}]_i = \frac{[TPVB_{x+1,n}]_i - [TPVB_{x,n}]_i}{[TPVC_{x+1,n}]_i - [TPVC_{x,n}]_i} \qquad (7.6)$$

where:

[IBCRx/x+1,n]i : Incremental benefit-cost ratio or the increments in benefit and cost between the lowest-ordered acceptable alternative x and the next higher-ordered one x+1for an n-year period and discount rate i
[TPVBx+1,n]i : Total discounted benefits for alternative x+1, an n-year period,

and discount rate i
[TPVCx+1,n]i : Total discounted costs for alternative x+1, an n-year period, and discount rate i

The interpretation of the result obtained from equation (7.6) is summarized in Table 6.

Table 6. INTERPRETATION OF RESULTS

Numerator and Denominator: positive	Numerator: positive; Denominator: negative	Numerator: negative; Denominator: positive	Numerator and Denominator: negative
When IBCR≥1.0, alternative x+1 will be more desirable than alternative x.	Alternative x+1 is always desirable than alternative x.	Alternative x is always desirable than alternative x+1.	When IBCR≤1.0, alternative x+1 will be more desirable than alternative x.
When IBCR<1.0, alternative x+1 will be rejected.			When IBCR>1.0, alternative x+1 will be rejected.

Investment Justification

Given the quantified benefits of pavement management by BCA in the previous subsection, it is possible to justify investment in PMS implementation using BCA that is used to justify the execution of a project. If the analysis concludes that the net benefit of PMS implementation, that is, monetized improvements on pavement management between before (without) and after (with) PMS implementation minus costs for PMS implementation is positive, PMS implementation is beneficial; otherwise, it should be terminated.

Table 7 defines an alternative for which benefits and costs can be measured in absolute terms using data that reflect the relative differences in benefits and costs in pavement management between before (without) and after (with) PMS implementation. The alternative uses incremental benefits of pavement management between before (or without) PMS implementation and after (or with) PMS implementation and costs for PMS implementation and then directly analyzes whether PMS implementation is beneficial in terms of efficiency.

Table 7. LIST OF ALTERNATIVE IN INVESTMENT JUSTIFICATION

Alternative	Data	Description
New alternative reported relative to status quo	Benefits and Costs reported in relative values	Pavement management after (with) PMS for existing highway system compared with before (without) PMS (status quo)

As explained in BCA in the previous subsection, we need to identify the benefits and costs related to asset management. Table 8 lists benefits and costs related to PMS implementation. The difference from Table 5 is the costs for PMS implementation considered in BCA for investment justification, because they are the costs of the analysis subject – PMS implementation.

Table 8. BENEFITS AND COSTS IN INVESTMENT JUSTIFICATOIN

Category		Description
Benefits	Agency	• Reduction in the cost of M&R
	User	• Savings in user costs, including travel time cost, vehicle operating cost, safety cost • Incremental user surplus
	External (non-user)	• Reduction in environmental costs, which are subjected to non-user.
Costs	Agency	• Costs for PMS implementation, including system price and overhead for system development and operation. The system includes database and analysis tools.

Once the alternative and benefits and costs are specified, benefits and costs need to be estimated to conduct BCA using the principles, elements, and methods addressed in BCA in the previous subsection. In addition, the following method can be used to determine when benefits of PMS implementation exceed costs if we cannot justify investment in PMS implementation.

- Internal Rate of Return Method

The internal rate of return (IRR) is the discount rate for which the discounted benefits over n years are exactly equal to the discounted costs. Hence, the IRR method tells us the discount rate at which benefits exceed costs. Also, if we cannot observe positive value in the net present value method or larger benefit-cost ratio than 1, the IRR method allows us to see when benefits exceed costs and how long it would take to pay off costs at a specific discount rate. This method includes two steps as follows:

- Step 0: Order alternatives in terms of increasing internal investment.
- Step 1: Determine the IRR for the lowest initial-year cost alternative (i.e., determine the IRR for alternative x=1).

For any alternative x, the IRR or r_x is the discount rate[6] that satisfies the following condition:

$$[TPVB_{x,n}]r_x = [TPVC_{x,n}]r_x,$$

or

$$\sum_{t=0}^{n} \frac{B_{x,t}}{(1+r_x)^t} = \sum_{t=0}^{n} \frac{C_{x,t}}{(1+r_x)^t} \qquad (7.7)$$

where $\frac{1}{(1+r_x)^t}$: discount factor for internal rate-of-return method

To ask whether the alternative is acceptable, a minimum attractive rate of return (MARR) that reflects the earning possibilities for foregone alternatives must be stated. If r_x is at least as large as the MARR, then alternative x is judged to be economically acceptable by this method.

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[6] If there are multiple solutions to equation (7.7) then the solution becomes quite complex. Park (1997) provides an in-depth treatment of the issue.

- Step 2: Determine the incremental internal rate of return for projects having an initial cost higher than the lowest initial cost alternative that is acceptable.

  If alternative x is the lowest acceptable initial cost alternative, then the incremental internal rate of return for the extra benefits and costs between x and the next higher initial cost alternative, x+1, must be determined.

  For alternative x+1 compared to alternative x, the incremental internal rate of return is that discount rate which satisfies the following identity:

$$[TPVB_{x+1,n}]r_{x/x+1} - [TPVB_{x+1,n}]\, r_{x/x+1} = [TPVC_{x+1,n}]r_{x/x+1} - [TPVC_{x+1,n}]\, r_{x/x+1}$$

or

$$\sum_{t=0}^{n} \frac{B_{x+1,t} - B_{x,t}}{(1 + r_{x/x+1})^t} = \sum_{t=0}^{n} \frac{C_{x+1,t} - C_{x,t}}{(1 + r_{x/x+1})^t} \qquad (7.8)$$

where $\frac{1}{(1 + r_{x/x+1})^t}$: discount factor for increment between x and x+1

If $r_{x/x+1}$, the internal rate of return on the increment, is at least as large as the MARR, then the alternative x+1 is accepted as better than x. If not, then the alternative x+1 is rejected, and a pairwise comparison is made between x and x+2, and so forth for successively higher-cost alternatives, until the highest initial cost alternative having satisfied both sets of rate-of-return calculations is determined.

Relationships between the Methods

The framework embraces the three analysis methods addressed above to obtain richer insight into PMS implementation as shown in Figure 11. The descriptive analysis identifies data consisting of various performance measures. The differences in the performance measures between before and after (with and without) PMS implementation show the benefits of PMS implementation in terms of efficacy, effectiveness, and efficiency as well as various trends of the agency's performance and exogenous effects. Then the data are entered into the regression analysis and BCA to quantify the benefits of PMS implementation in terms of monetary values as well as the performance measures. Since the regression analysis and BCA utilize before and after (with and without) data, they are under the umbrella of the descriptive analysis using before and after (with and without) data. Afterwards, the quantified benefits are used for justifying investment in PMS implementation with BCA in terms of efficiency.

The framework presents a direction for building a generic methodology for quantifying and evaluating the benefits of PMS implementation. From the analysis results, agencies can quantify the benefits of PMS and justify investment in PMS implementation.

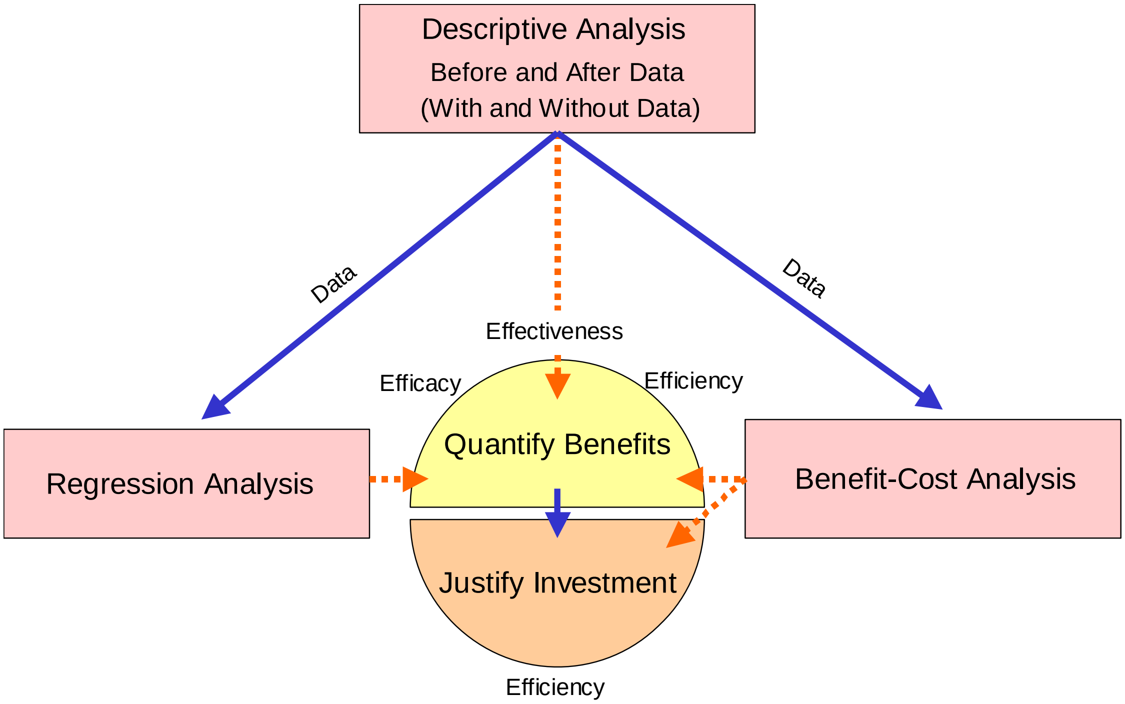

Figure 11. Concept of Methodology for Quantifying Benefits

3.2. Data Issues

The framework developed in the previous section relies on data on pavement conditions and related explanatory variables. As discussed, the type of evaluation design depends on the type of data available:

- Actual or simulated before and after performance data, or
- Actual or simulated with PMS performance data compared with simulated without PMS performance data.

These data are time series data and may be either pavement condition data for each section (disaggregate data) or average network performance data (aggregate data). The data disaggregated by section is panel data and presents some challenges. In order to build a generic methodology to quantify the benefits of implementing PMS, it is very important to recognize the following data issues.

Data Availability

The framework relies on data on pavement conditions, usage, section length, and expenditures. The data can be analyzed by road functional class (e.g., interstate, state, and local) to capture the effects of policy decisions. In using with and without data, a constant budget can be assumed to avoid consideration of expenditures. On the other hand, using before and after data should take into account expenditures. Since the benefits accrue over the years and may not be observed for several years, it is important to have data covering many years.

While the methods are not for a specific agency, the methods should be transferable and the framework uses data commonly collected in any agency. However, data availability will present some challenges in terms of access, format and quality, such as whether the data is open source, not confidential, and not in a proprietary format.

Spatial and Temporal Correlation

The pavement conditions of neighboring sections are likely to be highly correlated because these sections are subject to similar usage and environmental conditions and were often constructed at the same time. They are also temporally correlated for these same reasons. This problem is called autocorrelation. However, we are not interested in the condition of individual sections but the entire network condition. Aggregating the disaggregate data avoids these issues.

Data Quality

The quality of data is critical because it affects the results of analyses. It is important to ascertain: whether data are accurately collected and recorded in a consistent manner; whether data sources are reliable; and whether there are outliers in the data and why. Although many agencies have quality assurance programs, matching traffic volumes to pavement sections and checking for data errors are challenges (Hall, 2006). Common procedures, such exploratory data analysis and data mining, can be applied to address issues of data quality (Buchheit et al., 2005).

Valuation Method for User and External Costs

User costs include travel time cost, vehicle operating cost, and safety cost; and external costs include the costs of damages from vehicular emissions. The problem is that there are many valuation methods. Researchers use different methods to calculate the costs, and thus encounter different results. The method used should be the most appropriate for the particular agency and, where possible, the method should be consistent with that used in PMS. Also, we should be aware of what kinds of data are needed by the methods.

To illustrate the valuation methods used, the internationally and nationally recognized AMS, HDM-4 and HERS-ST, are compared to each other. For example, to obtain vehicle operating cost, vehicle speeds and operating resources are determined based on the characteristics of each type of vehicle and road geometry, pavement type and condition. Although HDM-4 considers both free flow and congested traffic conditions in the process, HERS-ST does free flow only. Also, they have different operating resources categories including fuel, oil, and tires from each other. In case of external costs, since HDM-4 investigates the impact of vehicle emissions on global warming and is mostly used in developing countries, HDM-4 considers carbon dioxide and lead, which are not taken into account by HERS-ST (Odoki and Kerali, 2000; Cambridge Systematics, 2005; U.S. DOT and FHWA, 2006a).

Simulation

As shown in Figure 8 and Figure 9, an *ex post facto* evaluation requires actual performance with PMS and predicted performance without PMS, while an *ex ante* evaluation requires predicted performance with PMS and predicted performance without PMS. To obtain the predicted performance without PMS in both evaluations, it is necessary to simulate M&R treatments based on an agency's strategy for selecting treatments without PMS. While many strategies are possible, a common strategy is the worst first strategy. This assumes that treatments will be applied to the sections in the worst condition.

If the PMS currently used in an agency allows input of M&R treatments based on a worst first strategy, it is easy to produce the predicted performance. Also, the predicted performance with PMS in *ex ante* evaluation can be simulated by PMS per se using the PMS's optimization strategy. In doing so, various performance measures required by the three analysis methods are outputs from the PMS analysis results. Otherwise, models used in PMS have to be transferred to an application such as a spreadsheet to simulate the predicted performance. Hence, it is imperative to investigate PMS functions in addition to data needed.

Chapter 4. CASE STUDIES

This chapter documents case studies that evaluate the implementation of two asset management systems using the framework including the three analysis methods identified in Chapter 3. The subjects of the case studies are the pavement management system (PMS) used in the Vermont Agency of Transportation (VTrans) and the Highway Economic Requirements System – State Version (HERS-ST) created by U.S. Department of Transportation and Federal Highway Administration applied to data from New Mexico. Each case presents system background, analysis methods, analysis results, lessons learned, and a summary.

4.1. VTrans Case Study

This section presents a case study of VTrans. The objective of the VTrans' data analysis is to recognize the benefits[7] in terms of improved pavement conditions between a strategy based on PMS and a worst first strategy. The analysis is based on forecasted data under the assumption that VTrans uses PMS and simulated data representing a scenario generated to approximate a series of decisions without PMS based on the worst first strategy.

VTrans

Vermont is located in New England, which is in the Northeastern part of the United States. Vermont shares borders with Canada, New York, Massachusetts, and New Hampshire. VTrans is in charge of various transportation modes such as roads, air, railroads, and public transit. VTrans manages 2,708 miles of highways (320 miles of interstate, 2,388 miles of state highways). Towns manage 8,654 miles of roads and streets although VTrans paves 135 miles of these roads. VTrans also manages 2,675 Bridges (313 Interstate bridges, 764 state highway bridges, and 1,598 town bridges). Currently, the average Pavement Condition Indices[8] for interstate and state highways in Vermont are 77 and 70, respectively. Vermont has 16.9 percent of long structures[9] structurally deficient, while the national average is 13.7 percent (VTrans, 2006a; 2006b).

VTrans started examining performance measures several years ago, and asset management was an outgrowth of it. The State House Transportation Committee was also interested in asset management and encouraged the introduction of state legislation in July 2001. VTrans supports this legislation and considers it an opportunity to focus on a program for an asset class rather than on individual projects. VTrans presents an asset management plan as the Fiscal Year Budget Narrative to the House and Senate Transportation Committees. If the Committees do not accept the plan as is, VTrans has to submit a revised plan for approval (VTrans, 2004a).

Referring to the needs (i.e., regulation, guidelines, and articulation of the 3Es) described in Chapter 3, VTrans satisfies them using their resources and opportunities. As described above, the state of Vermont passed the legislation that requires VTrans to submit an asset management plan to the Committees. In order to comply with the legislation and further develop asset management, VTrans has enthusiastically participated in conferences and meetings while sharing their experiences with others. Furthermore, VTrans articulates the improvements to asset

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[7] Benefits can be recognized by the 3Es described in Section 0 in APPENDIX B.

[8] Pavement Condition Index (PCI) is based on pavement's distress type, distress quantity, and distress severity.

[9] Long structures are anything, including bridges, pipes, or culverts, 20 feet or longer (VTrans, 2007a).

condition using performance measures via periodical reports to the Committees and public. However, they may have difficulty articulating the efficiency of AMS implementation, which is, justifying investment in AMS implementation.

Pavement Management System in VTrans

VTrans uses the Deighton Total Infrastructure Management System (dTIMS^{TM}CT) software as the PMS. The dTIMS™CT has the following function components:

Database

dTIMS™CT includes a pavement database. The data consists of information such as rutting, ride (measured as the International Roughness Index – IRI), wheel pass cracking, non-wheel pass cracking, transverse cracking, average daily traffic, and age of last treatment. The data does not contain skid resistance (VTrans, 2004b).

Analysis Tools

dTIMS™CT enables users to analyze the data based on a variety of maintenance and rehabilitation treatment alternatives over a period of time. The PMS is capable of all of the following:

- Exploring capital versus maintenance tradeoffs,
- Analyzing projects on the basis of life-cycle agency costs and benefits estimated by the area under pavement performance curve which is a measure of the difference between doing nothing and the treatment effect on pavement condition in terms of composite index (CMP) described below. The area is multiplied by a traffic-weighting factor to include a user component for optimizing M&R treatments. This is based on a concept to distribute benefits (i.e., improvement of pavement condition) to road users in addition to agency per se.
- Analyzing the impacts of alternative programs on system performance, and
- Generating information on the level of expenditure needed to meet target condition levels.

However, no tools exist that can perform tradeoffs across program categories in VTrans (VTrans, 2004b).

Performance Model

A pavement performance model is employed in dTIMS™CT to predict future conditions. Based on data gathered by survey, the model calculates a deterioration rate for pavement and forecasts when repair is needed.

Condition Measures

The CMP variable is derived from alligator cracking index, longitudinal cracking index, smoothness index, and rut depth index calculated by dTIMS™CT. The definition of rating using CMP is as follows:

Very poor: $0 \leq \text{CMP} < 40$, Poor: $40 \leq \text{CMP} < 65$, Fair: $65 \leq \text{CMP} < 80$, Good: $\text{CMP} \geq 80$

Reporting

dTIMS™CT provides summary reports using tools such as GIS and statistical analysis (Deighton, 2004).

Analysis Method

In Section 3.1, three methods are presented: descriptive analysis using before and after (with and without) data, regression analysis, and benefit-cost analysis. In order to conduct analysis using the methods, two evaluation methods, *ex post facto* and *ex ante*, can be applied to recognize the efficacy in pavement conditions between before and after PMS implementation in this case study. Actual data, which are derived from survey or monitoring, showing performances such as pavement conditions and M&R costs before and after PMS implementation, are needed. However, it is difficult to determine when PMS was implemented because VTrans incrementally prepared and implemented PMS over the last two decades. Hence, this case study cannot apply *ex post facto* evaluation that uses a comparison of actual pavement conditions between before and after PMS implementation or a comparison between predicted conditions without PMS and actual condition after PMS implementation. Also, VTrans does not have complete data related to the implementation of PMS, especially costs used for PMS implementation due to the difficulty of extracting PMS implementation costs combined with various expenditures. When using *ex ante* evaluation, the lack of PMS implementation costs may prevent the calculation of BCA.

To conduct *ex ante* evaluation, this case study utilizes two different datasets provided by VTrans. The datasets represent simulated scenarios based on PMS's strategy using dTIMS's optimization (i.e., 'with PMS case') and a worst first strategy (i.e., 'without PMS case') as follows (VTrans, 2006c; VTrans, 2006d):

- Access database that includes predicted pavement condition as a result of M&R treatments recommended by dTIMS™CT. Four treatments (i.e. thin overlay, level and overlay, pulverize and overlay, and reconstruction) are considered; and
- Excel spreadsheet that includes pavement condition as a result of M&R treatments created by VTrans based on a worst first strategy. Section data and do-nothing composite index values were imported from dTIMS™CT. Treatments used were level and overlay; costs were calculated using the same expression as in dTIMS™CT.

The datasets are panel data representing data for 4015 road elements over 14 years from 2006 to 2019. The datasets use a budget constraint of $55 million over 14 years; consistent traffic growth for each scenario; and assume no new construction in Vermont. We use the term 'elements' to be consistent with VTrans definitions. In this case study, an element is synonymous with a section in the methodology in Chapter 3. Since the datasets are based on the same conditions of traffic volume, budget constraints, and network length over the analysis period, there is no need to control those variables. The variables in the datasets are described in APPENDIX C.

There are three road pavement classes: Interstate (INT), State System (STE), and Class 1 (CL1)[10]. Table 9 summarizes road network conditions in 2006. Figure 12 and Figure 13 graphically represent the pavement condition in terms of number of elements and lengths. The majority of the network belongs to the State System and a large portion of this system is in very poor and poor conditions although the distribution of its elements is positively skewed (i.e., toward good condition). The second largest class in the network is the Interstate System and its

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[10] Class 1 represents town highways which form the extension of a state highway route and which carry a state highway route number (VTrans, 2007b).

distribution is positively skewed in terms of number of elements and is equally distributed in terms of lane-miles. CL1 is smallest class and most elements belong to fair and good conditions in lane-miles.

Table 9. ROAD NETWORK CONDITION IN 2006

Road Pavement Class		*Elements (Lengths: lane-miles)*				
		Very Poor	Poor	Fair	Good	Total
Interstate	(INT)	56 (292.86)	178 (346.13)	149 (278.92)	274 (361.54)	657 (1,279.45)
State System	(STE)	261 (588.83)	953 (1,475.35)	1,048 (1,637.12)	822 (1,099.80)	3,084 (4,801.10)
Class 1	(CL1)	28 (0)	163 (31.78)	130 (181.99)	43 (297.83)	364 (511.59)
Total		345 (881.69)	1,294 (1,853.26)	1,327 (2,098.03)	1,139 (1,759.17)	4,105 (6,592.14)

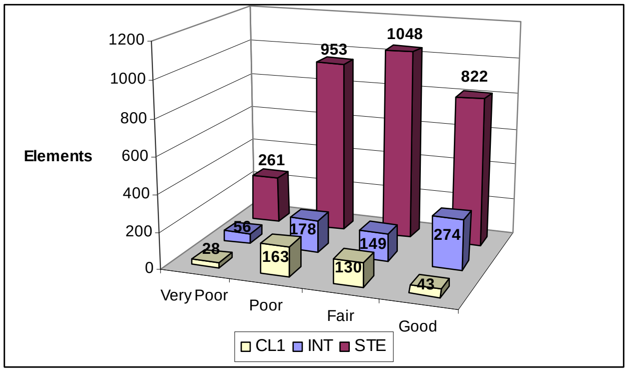

Figure 12. Numbers of elements based on condition

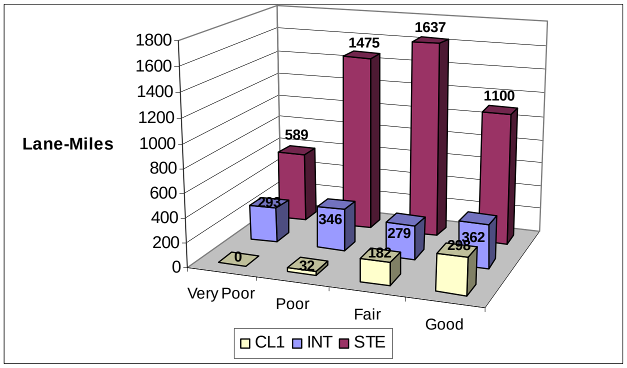

Figure 13. Lengths of elements based on condition

In the following subsections, the calculation methods to obtain pavement conditions using the datasets are presented. Various aggregate measures of network conditions are used. These measures capture the network performance and do not have the issues of spatial and temporal correlation present in the raw panel data. Also, the analysis methods to quantify the benefits of PMS implementation and to justify investment in PMS implementation addressed are explained in terms of how they are applied to this case study using the datasets.

Benefit Quantification

For quantifying the benefits of PMS implementation, the methods identified in Section 3.1 are used to articulate the 3Es of PMS implementation as follows:

Descriptive Analysis Using Before and After (With and Without) Data

Before and after tries to identify whether and how much an agency's performance is improved from the condition without PMS to that with PMS. Since this case study employs an *ex ante* evaluation that simulates the before and after performances using the datasets, we call it 'with and without.' We can observe performance measures between the 'with' and 'without' cases. It is hypothesized that the performance measures with PMS are superior to those without PMS. This result demonstrates that the efficacy and efficiency derived from PMS improve VTrans' performance. Also, the comparison of the ratios of improvements of pavement conditions to the costs for M&R treatments between 'with' and 'without' can identify the efficiency.

Using the two datasets described in APPENDIX C, the two kinds of pavement performance measures are calculated to conduct the descriptive analysis using with and without data as follows:

- Average pavement condition by year (Scale: 0-100)

$$\text{Average Pavement Condition} = \frac{\sum_{i=1}^{4105}(CMP_i \times Length_i)}{\sum_{i=1}^{4105} Length_i} \qquad (8.1)$$

where:

CMP : Composite index variable derived from four individual distress indices (alligator cracking index, longitudinal cracking index, smoothness index, and rut depth index)
Length : Length of road elements in mile
i : Road element's number (i = 1, …, 4105)

- Traffic weighted average pavement condition by year (Scale: 0-100)

$$\text{Traffic Weighted Average Pavement Condition} = \frac{\sum_{i=1}^{4105}(CMP_i \times AADT_i \times Length_i)}{\sum_{i=1}^{4105}(AADT_i \times Length_i)} \qquad (8.2)$$

where:

CMP : Composite index variable
AADT : Annual average daily traffic
Length : Length of road elements in mile
i : Road element's number

Also, two additional measures are used to see trend of pavement condition over the analysis period as follows:

- Percent length by condition by year
  e.g., for Very Poor

$$\text{Percent Length by Very Poor} = \frac{\sum_{j=J}^{4015} Length_j}{\sum_{i=1}^{4015} Length_i} \times 100\,,\ \forall j = VeryPoor \qquad (8.3)$$

Besides very poor, there are poor, fair, and good conditions.

- Percent travel by condition by year
  e.g., for Very Poor

$$\text{Percent travel by Very Poor} = \frac{\sum_{j=J}^{4015}(Length_j \times AADT_j)}{\sum_{i=1}^{4015}(Length_i \times AADT_i)} \times 100,\ \forall j = VeryPoor \qquad (8.4)$$

Besides very poor, there are poor, fair, and good conditions.

Furthermore, effectiveness, the net area under the curve (the area under the curve with PMS minus the area under the curve without PMS) multiplied by traffic volume and length of road elements, is calculated as follows:

$$\text{Effectiveness} = \sum_{i=1}^{4105}\sum_{t=2006}^{2019}\left\{(CMP_{i,t}^{w/PMS} - CMP_{i,t}^{w/oPMS}) \times AADT_{i,t} \times Length_i\right\} \qquad (8.5)$$

where:

CMP : Composite index variable
AADT : Annual average daily traffic
Length : Length of road elements in mile
i : Road elements' number (4105 elements)
t : Year (2006 to 2019)

Regression Analysis

Regression analysis models the relationships between variables and provides the degree of independent variables' influence on a dependent variable by coefficients. Because budget constraints and network lengths are consistent, the possible models are as follows:

Model 1: Average Pavement Condition$_t$ = f (AADT $_t$, PMS $_t$)
Model 2: Traffic Weighted Average Pavement Condition$_t$ = f (AADT $_t$, PMS $_t$)

where:

For t =2006,…, 2019
Average Pavement Condition (APC) $_t$: Average pavement condition in year t
Traffic Weighted Average Pavement Condition (TWAPC) $_t$: Traffic weighted average pavement condition in year t
AADT $_t$: Total annual average daily traffic in all road elements in year t
PMS $_t$: Use of PMS in year t (dummy variable: 1- yes; 0-no)

In order to recognize the efficacy and effectiveness of PMS, the regression analysis uses aggregate data from 2006 to 2019 listed in Table 10. If the result shows a positive and significant coefficient for the variable, PMS, the implementation of PMS is assumed to have efficacy to improve pavement conditions. Also, the degree of the coefficient shows effectiveness and efficiency (since 'with' and 'without' cases have the same amounts of a budget constraint).

Benefit-Cost Analysis

Using the methods addressed in Section 3.1, BCA is used to quantify the benefits of PMS implementation. Usually the benefits and negative benefits (i.e., costs) addressed in Table 5 should be taken into account as benefits such as savings in user costs consisting of vehicle operation, safety, and travel time, and reduction in agency costs including manpower, equipment, and materials for M&R treatments. Furthermore, a reduction in external costs for socio-environmental damage caused by energy consumption from non-users' perspective would be included in the benefits. This case study, however, will not deal with the benefits because the two simulated datasets for 'with case' and 'without case' are based on the same condition: budget constraints that affect agency costs, and AADTs and network lengths that affect user and external costs. There would be differences in agency and user costs between 'with case' and 'without case' if we look closely at those costs affected by different M&R treatments derived from PMS and a worst first strategy. For example, PMS implementation may optimize M&R treatments within the constrained budget and allow improving pavement condition better than the worst first strategy. Then, the user needs less vehicle operating costs and safety costs due to smooth surfaces. Since there is no available data, however, this case study will not explore these benefits. We assume that there are no explicit benefits in terms of savings in user costs, reduction in agency costs, and reduction in external costs because of the same condition between 'with' and 'without' cases.

Table 10. DATA FOR REGRESSION ANALYSIS

Year	*APC*	*TWAPC*	*AADT (000)*	*PMS*
2006	68.0	69.5	25,328	0
2006	63.1	65.1	25,328	1
2007	65.4	66.7	25,328	0
2007	65.3	70.5	25,328	1
2008	62.8	64.1	25,807	0
2008	61.1	69.7	25,807	1
2009	60.3	60.4	26,285	0
2009	56.6	69.0	26,285	1
2010	58.4	57.1	26,764	0
2010	51.9	68.4	26,764	1
2011	56.6	54.0	27,242	0
2011	48.2	67.0	27,242	1
2012	55.6	51.8	27,721	0
2012	45.7	65.6	27,721	1
2013	55.1	50.3	28,199	0
2013	44.5	64.9	28,199	1
2014	54.7	49.7	28,678	0
2014	44.0	64.3	28,678	1
2015	54.3	49.4	29,156	0
2015	44.0	64.1	29,156	1
2016	53.3	50.0	29,634	0
2016	43.7	63.5	29,634	1
2017	52.7	50.9	30,113	0
2017	43.2	63.0	30,113	1
2018	51.5	52.9	30,591	0
2018	43.2	63.6	30,591	1
2019	50.4	56.1	31,070	0
2019	42.8	65.9	31,070	1

Note: APC = average pavement condition; TWAPC = traffic weighted average pavement condition

Investment Justification

To determine whether the benefits of PMS implementation exceed PMS implementation and operation costs, we need to perform BCA again. As described above, however, agency, user, and external benefits will not be dealt with by the previous BCA. If cost data were available, the agency benefits could be used. Furthermore, to justify investment in PMS implementation, costs for PMS implementation are required to conduct the net present value method and a denominator in the benefit-cost ratio method. Since no implementation costs are available, it is not possible to justify investment in PMS implementation in this case study.

Analysis Results

Based on the analysis methods described in Section 3.1, we focus on quantifying the benefits of PMS implementation in this case study as follows:

Descriptive Analysis Using With and Without Data

Figure 14 to Figure 21 show pavement conditions in terms of a composite index that takes into account alligator cracking, longitudinal cracking, smoothness, and rut depth, over 14 years, in terms of average pavement condition and traffic weighted average pavement condition based on with PMS and without PMS. The figures represent pavement conditions for all road pavement classes: Interstate (INT: Figure 15 and Figure 19), State System (STE: Figure 16 and Figure 20), and Class 1 (CL1: Figure 17 and Figure 21).

Focusing on the average pavement condition, we recognize that the condition without PMS is better than that with PMS except for the Interstate class. However, focusing on the traffic weighted average pavement condition, the condition with PMS is better than that without PMS in all classes. Table 11 shows the relationship using means of the average conditions over 14 years to summarize the results presented in Figure 14 to Figure 21. Depending on the focus either on the average pavement condition or on the traffic weighted average pavement condition, we have a completely different picture for evaluation. With large traffic volume on a road element, pavement condition of this element would be worse than that of another element with small traffic volume. Pavement conditions depend on the traffic effect. Hence, the result of the traffic weighted average pavement condition is more appropriate than that of the average pavement condition to distinguish the efficacy of PMS by taking into account the traffic effect.

With PMS

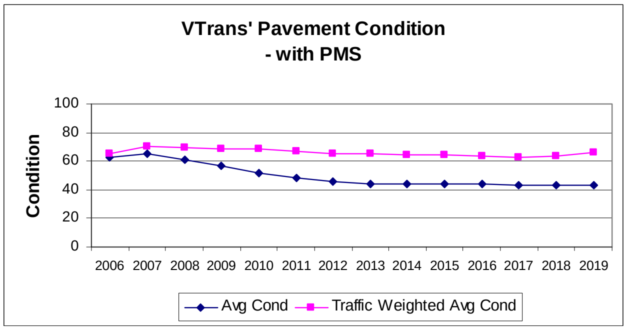

Figure 14. Pavement condition with PMS (All)

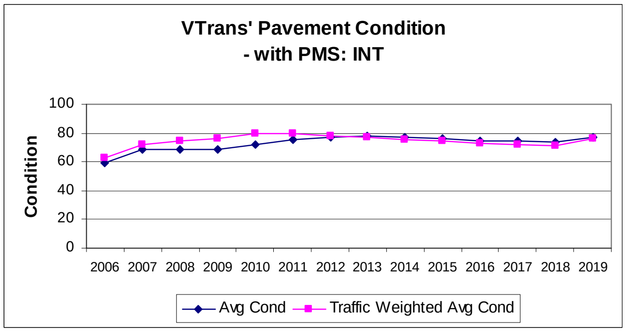

Figure 15. Pavement condition with PMS (INT)

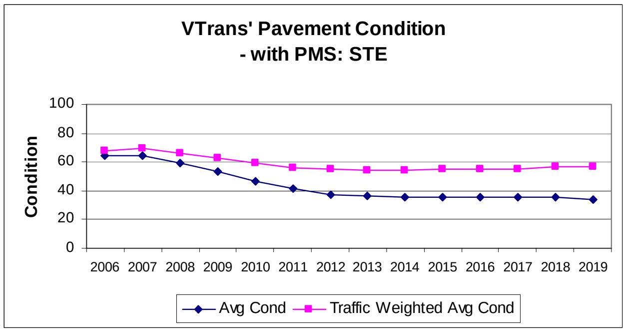

Figure 16. Pavement condition with PMS (STE)

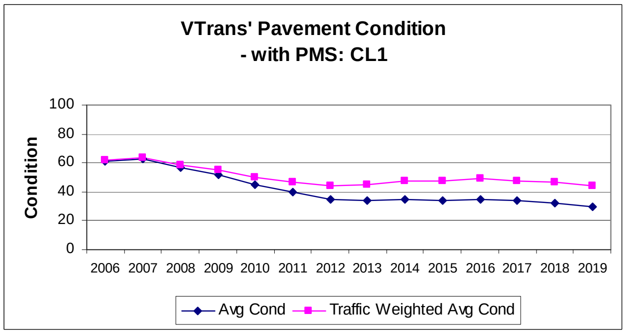

Figure 17. Pavement condition with PMS (CL1)

Without PMS (worst first strategy)

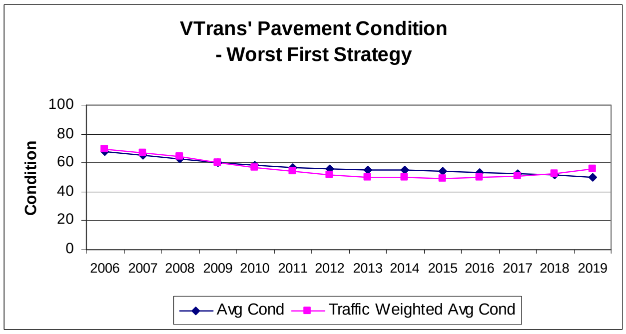

Figure 18. Pavement condition without PMS (All)

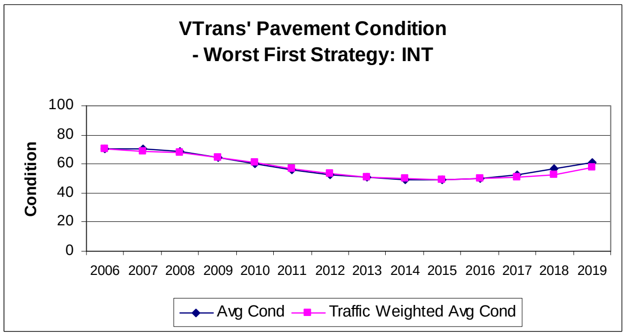

Figure 19. Pavement condition without PMS (INT)

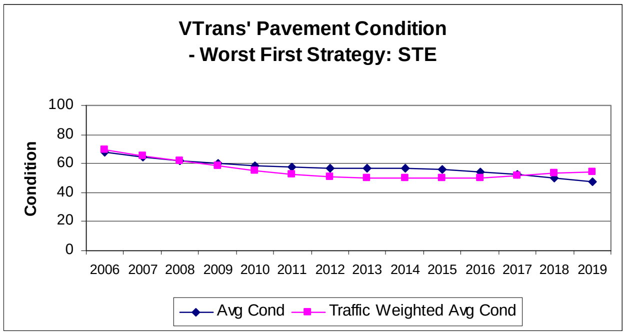

Figure 20. Pavement condition without PMS (STE)

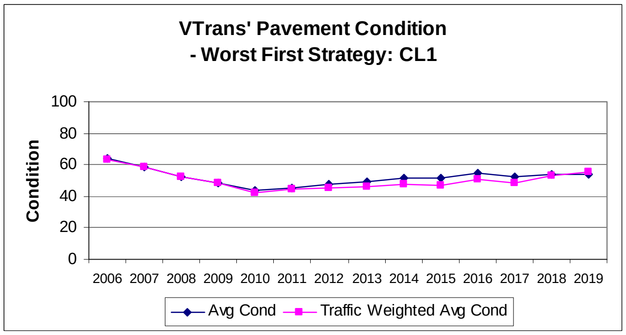

Figure 21. Pavement condition without PMS (CL1)

Table 11. MEANS OF AVERAGE PAVEMENT CONDITION OVER 14 YEARS

Pavement Class	Average Condition			Traffic Weighted Average Condition		
	With PMS	Without PMS	Difference (w/-w/o)	With PMS	Without PMS	Difference (w/-w/o)
All	49.8	57.1	-7.3	66.0	55.9	10.1
Interstate	72.8	57.9	14.9	72.9	57.9	15.0
State	44.0	57.1	-13.1	58.9	55.1	3.8
CL1	41.8	52.0	-10.2	50.5	50.2	0.3

Now, we focus on the traffic weighted average conditions shown in Figure 22 to Figure 25. The conditions for all pavement classes with PMS are better than those without PMS from 2007 to 2019 using the same budget. For all road classes, the mean of the traffic weighted average condition with PMS is 10.1 points (=66.0-55.9) higher than that without PMS as Table 11 shows. The increase is equivalent to 18 percent (=10.1/55.9) of the traffic weighted average condition without PMS.

The traffic weighted average condition without PMS is better than that with PMS in 2006. This may result from the effect of a treatment being selected in the first year. After year 2006, the condition with PMS exceeds that without PMS.

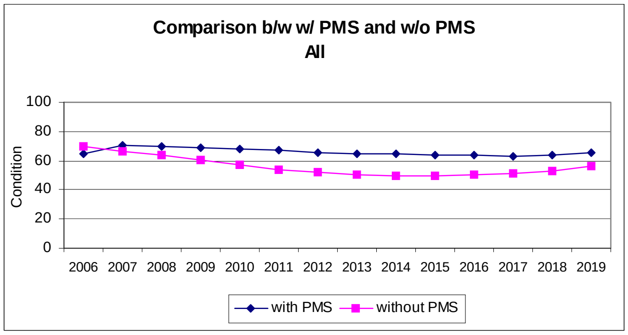

Figure 22. Comparison of traffic weighted average pavement conditions (All)

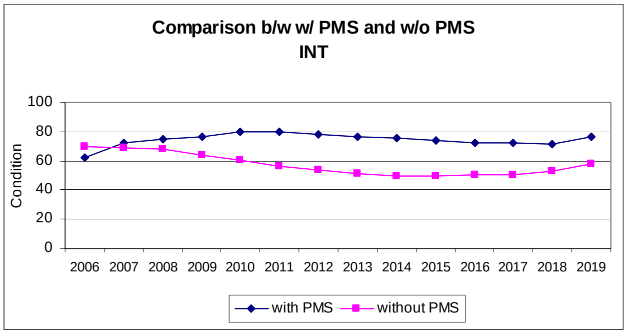

Figure 23. Comparison of traffic weighted average pavement conditions (INT)

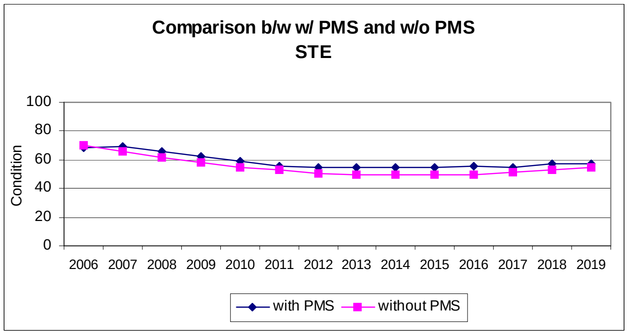

Figure 24. Comparison of traffic weighted average pavement conditions (STE)

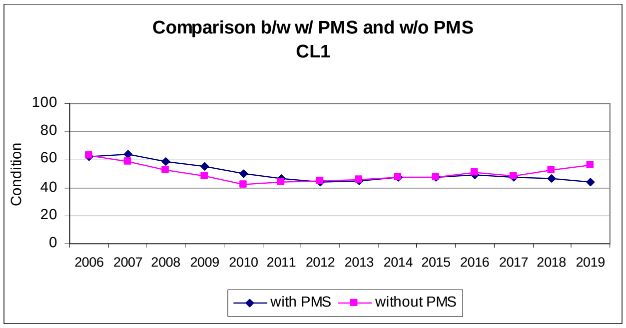

Figure 25. Comparison of traffic weighted average pavement conditions (CL1)

The traffic weighted average condition of the Interstate with PMS significantly contributes to the overall condition except in 2006 compared to State System and Class 1. Although one might expect the increase in pavement conditions to be due to the larger traffic volume on Interstates, the volume on Interstates is actually less than that on the State System as Figure 26 shows. Hence, it is assumed that PMS prioritizes M&R treatments for Interstate rather than State System and Class 1 because of road type hierarchy. Otherwise, M&R treatments for the State System cannot catch up with the pace of deterioration in the system because the system already holds 76 percent of the total length of poor and very poor conditions (Interstate: 23%, CL1: 1%). Compared to the Interstate, it may be difficult to significantly improve conditions in the State System.

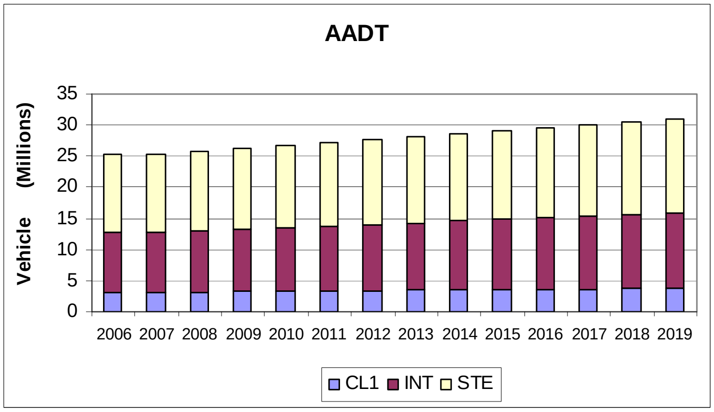

Figure 26. AADT based on road class

As discussed above, because the traffic weighted average condition is more appropriate to distinguish the efficacy of PMS, the focus is on percent travel by pavement conditions drawn in Figure 27 to Figure 34 rather than percent length by pavement condition here. Figures of percent length by pavement conditions are included in APPENDIX D. Large differences are observed in the Interstate road class. That is, the portion of good pavement condition with PMS is significantly larger than that without PMS. This situation is shown in Table 12, which shows that the mean of the percent of good condition with PMS is 27 percent (=58%-31%) higher than that without PMS. The fair and good conditions with PMS are relatively better than those without PMS in State Systems and Class 1.

With PMS

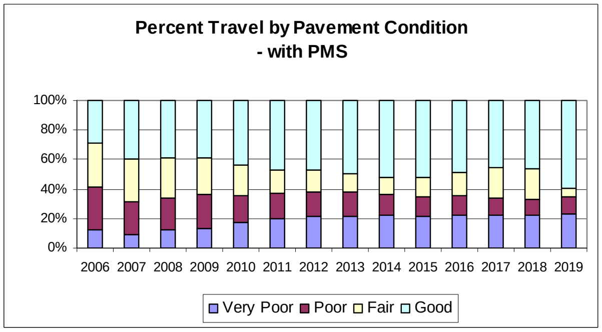

Figure 27. Percent travel by condition with PMS (All)

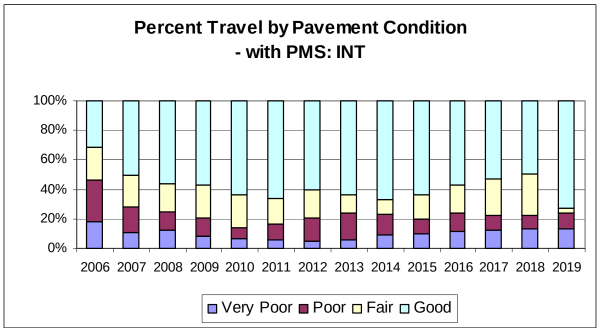

Figure 28. Percent travel by condition with PMS (INT)

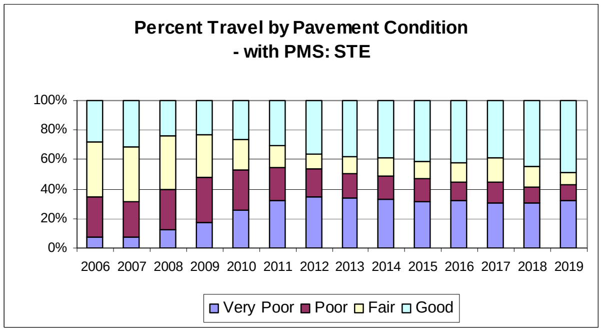

Figure 29. Percent travel by condition with PMS (STE)

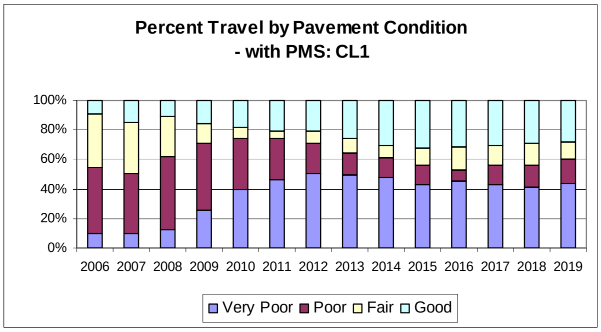

Figure 30. Percent travel by condition with PMS (CL1)

Without PMS (worst first strategy)

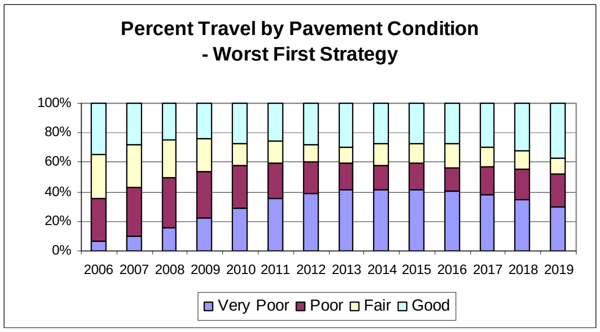

Figure 31. Percent travel by condition without PMS (All)

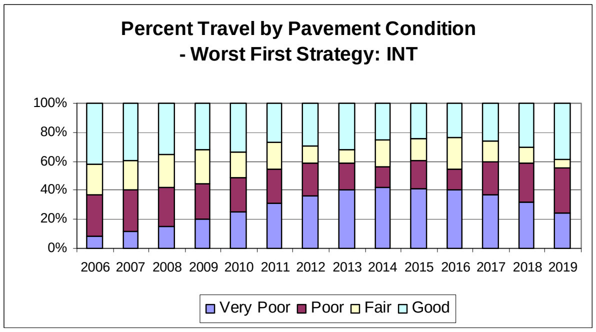

Figure 32. Percent travel by condition without PMS (INT)

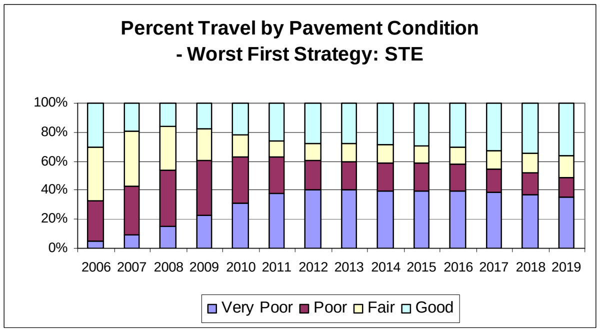

Figure 33. Percent travel by condition without PMS (STE)

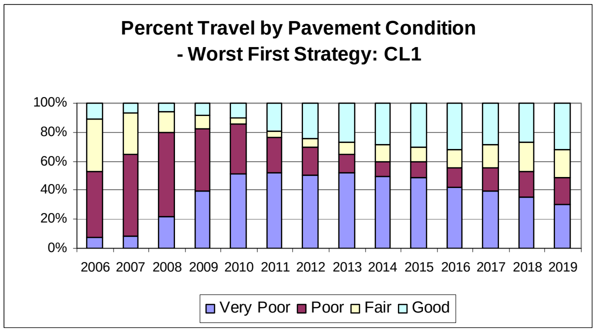

Figure 34. Percent travel by condition without PMS (CL1)

Table 12. MEAN OF PERCENT TRAVEL BY PAVEMENT CONDITION OVER 14 YEARS

Pavement Class	With PMS				Without PMS			
	Very poor	Poor	Fair	Good	Very poor	Poor	Fair	Good
All	19%	17%	19%	46%	30%	24%	17%	29%
Interstate	10%	14%	18%	58%	29%	23%	17%	31%
State	26%	20%	19%	35%	31%	24%	18%	27%
CL1	36%	26%	15%	23%	38%	27%	14%	21%

The effectiveness of all pavement classes identified by the comparison between ‘with case’ and ‘without case’ scenarios using equation (7.3) is shown in Figure 36. Similar to pavement conditions addressed in the descriptive analysis, the products of CMP, AADT, and section length of ‘with case’ are higher than those of ‘without case’ from 2007 to 2019. The value of ‘with case’ increases over 14 years, while that of ‘without case’ forms a concave curve. It is obvious that PMS implementation produces positive effectiveness. From Table 13 and Table 14, the effectiveness of all road pavement classes is 3,059 (= 19,480–16,421) and represents a 19 percent increase (=(19,480–16,421)/16,421) in effectiveness between ‘with’ and ‘without’ cases.

Figure 35, Figure 38, and Figure 37 depict the effectiveness of Interstate, State System, and Class 1, respectively. As can see, the Interstate System (31 percent) significantly contributes to the increase of the effectiveness for all pavement classes compared to the State System (7 percent) and Class 1 (0 percent). Class 1 has no change in effectiveness caused by PMS implementation over 14 years. In the figures, the areas filled with dots represent decreases in the effectiveness caused by PMS implementation, while the areas filled with diagonal lines represent increases in the effectiveness.

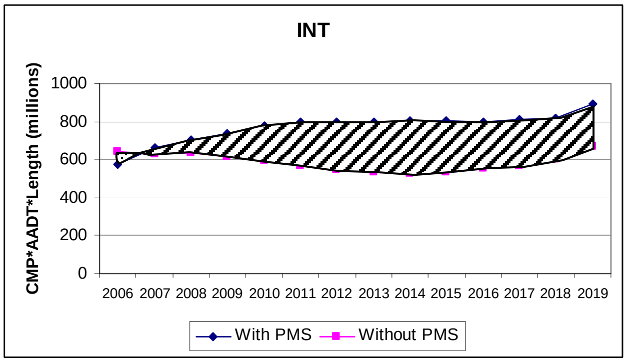

Figure 35. Effectiveness (INT)

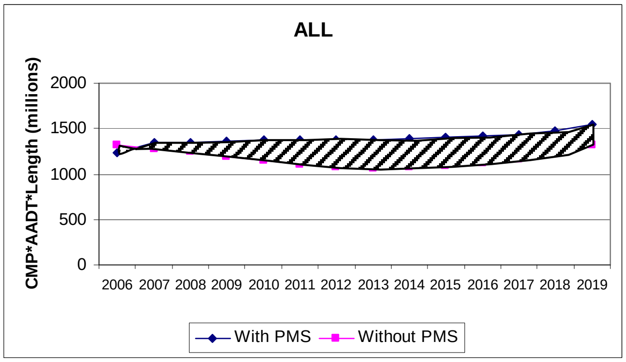

Figure 36. Effectiveness (All)

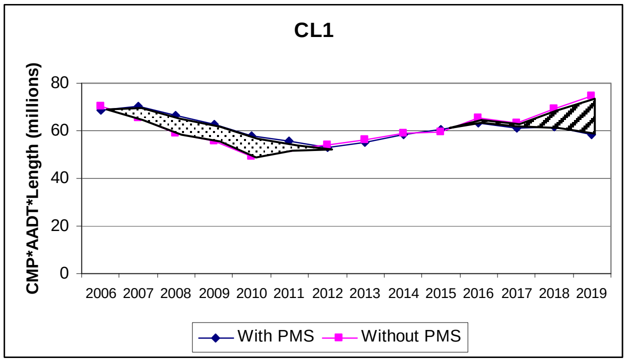

Figure 37. Effectiveness (CL1)

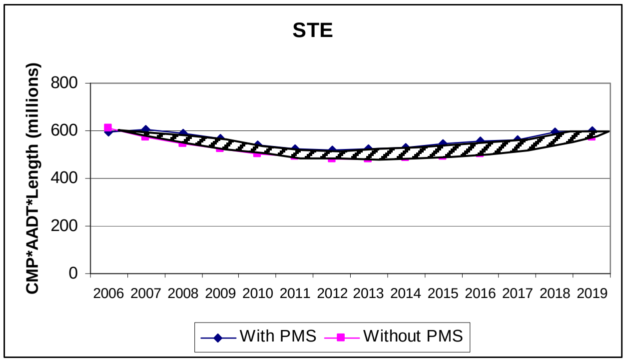

Figure 38. Effectiveness (STE)

Table 13. PERFORMANCE WITH PMS

	CMP*AADT*Length (millions)			
Year	INT	STE	CL1	ALL
2006	575	596	69	1,239
2007	664	608	71	1,342
2008	700	587	66	1,353
2009	735	567	63	1,365
2010	780	541	58	1,379
2011	797	522	56	1,375
2012	799	519	53	1,371
2013	800	525	55	1,380
2014	801	532	59	1,392
2015	804	547	60	1,411
2016	800	558	63	1,421
2017	808	563	61	1,433
2018	816	592	62	1,470
2019	889	600	59	1,548
Total	10,770	7,857	853	19,480

Table 14. PERFORMANCE WITHOUT PMS

	CMP*AADT*Length (millions)			
Year	INT	STE	CL1	ALL
2006	645	609	70	1,324
2007	632	573	65	1,270
2008	637	548	59	1,244
2009	615	525	56	1,195
2010	596	505	49	1,150
2011	565	492	53	1,109
2012	547	482	54	1,083
2013	533	481	56	1,070
2014	529	486	59	1,074
2015	534	492	59	1,086
2016	551	502	65	1,119
2017	568	525	63	1,157
2018	602	552	69	1,224
2019	670	572	75	1,317
Total	8,224	7,344	853	16,421

We consider the effectiveness to be unit-less. To illustrate how this value can be converted to monetary terms, we assume that users are willing to pay $2 per year for each unit of improvement in CMP and that on average each user drives 12,000 miles per year; the value of benefits over the 14 year period is about $360,000 (Table 15), using a discount rate of 4 % as follows:

Value of Improvement =

$$\sum_{t=2006}^{2019} \frac{\sum_{i=1}^{4105} \left\{ CMP_{i,t}^{w/PMS} - CMP_{i,t}^{w/oPMS}) \times AADT_{i,t} \times Length_i \right\} \times Unit\_WTP}{(1+r)^{(t-2006)}} \tag{8.6}$$

where:

CMP	:	Composite index variable
AADT	:	Annual average daily traffic
Length	:	Length of road elements in mile
i	:	Road elements' number (4105 elements)
t	:	Year (2006 to 2019)
Average Mileage	:	12,000 miles per year
Willingness to Pay	:	$ 2 per year for each unit of CMP improvement in their driving
Unit WTP	:	$ 0.00017 per miles-year (=$2/12,000 miles) for each unit of CMP improvement in their driving
Discount Rate	:	4 %

Table 15. VALUE OF IMPROVEMENT IN EFFECTIVENESS

Year	CMP*AADT*Length (millions)		Value of Improvement
	with	without	
2006	1239	1324	$ (14,167)
2007	1342	1270	$ 12,000
2008	1353	1244	$ 18,167
2009	1365	1195	$ 28,333
2010	1379	1150	$ 38,167
2011	1375	1109	$ 44,333
2012	1371	1083	$ 48,000
2013	1380	1070	$ 51,667
2014	1392	1074	$ 53,000
2015	1411	1086	$ 54,167
2016	1421	1119	$ 50,333
2017	1433	1157	$ 46,000
2018	1470	1224	$ 41,000
2019	1548	1317	$ 38,500

NPV	$ 360,592

Regression Analysis

The regression analysis focused on the traffic weighted average pavement condition as discussed in the descriptive analysis. Figure 39 depicts the relationship between the traffic weighted average pavement condition and the AADT in each year using the numbers in Table 15. Because AADT increases as the year goes on, the figure is similar to Figure 22 which show the comparison between ‘with case’ and ‘without case’ scenarios for all pavement classes.

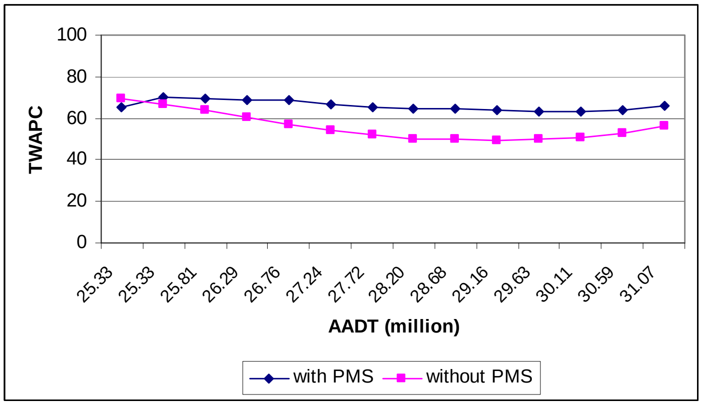

Figure 39. Relationship between traffic weighted average pavement condition and AADT

Because of the concave curves of the traffic weighted average condition with respect to AADT in Figure 39, this case study used a quadratic regression model:

Let TWAPC $_t$ be the traffic weighted average pavement condition in year t, t = 2006,…, 2019, AADT $_t$ be the total annual average daily traffic (unit: thousand) in all road elements in year t, and PMS $_t$ be the use of PMS in year t. The model to be estimated is:

$$TWAPCt = \beta_0 + \beta_1 AADT_t + \beta_2 (AADT_t)^2 + \delta_{1t} PMS_t + \varepsilon_t \qquad (8.7)$$

where:

β_0, β_1, and δ_{1t} : Parameters

ε_t : Error term associated with the t th traffic weighted average condition

δ_{1t} : Coefficient for the dummy variable
e.g., δ_{1t} is equal to 1 if PMS is used in year t and equal to 0 otherwise

The following results are obtained (standard errors are drawn in parentheses):

$$\hat{T}WAPC_t = 715.8 - 0.0454 AADT_t + (7.7E-07) AADT_t^2 + 10.1 PMS_t \quad (8.8)^{11}$$

$$(144.67) \quad (0.01) \qquad\qquad (0) \qquad\qquad (1.10)$$

R-Square = 0.854, RMSE = 0.041

Intercept (β_0) : t value = 4.95 ; P value < 0.001
AADT (β_1) : t value = - 4.39 ; P value < 0.001
AADT^2 (β_2) : t value = 4.22 ; P value < 0.001
PMS (δ_{1t}) : t value = 9.21 ; P value < 0.001

The detailed Excel printouts are included in Figure 40.

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.924
R Square	0.854
Adjusted R Square	0.835
Standard Error	2.911
Observations	28

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	1186.0894	395.3631	46.67	3.61E-10
Residual	24	203.3216	8.4717		
Total	27	1389.4111			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	715.835	144.674	4.948	4.744E-05	417.242	1014.428
AADT	-0.045	0.010	-4.393	0.000	-0.067	-0.024
AADT^2	7.778E-07	1.842E-07	4.222	0.000	3.976E-07	1.158E-06
PMS	10.134	1.100	9.211	2.384E-09	7.863	12.404

Figure 40. Excel Outputs

Since the quadratic model (8.8) shows high R-Square and all coefficients are significant, it is acceptable. It is noted that the model is applicable when AADT is between 25,328,447 and 31,069,773. The model indicates that the use of PMS improves traffic weighted average pavement condition at 10.1 points. This is consistent with the average improvement estimated in the descriptive analysis using with and without data. Given that the AADT is the same in both cases, this result is expected. The maximum (best) condition based on the model is about 73.9

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[11] 'E-07' represents seven decimal places. Hence, '7.7E-07' means '0.00000077.'

points when considering AADT in year 2006 for 'with case.' Since this model uses aggregate data derived from panel data, this model can avoid a problem of autocorrelation.

Lessons Learned

The case study emphasizes the challenges and realities of obtaining data before and after PMS implementation to support descriptive analysis. However, simulated datasets can be used in a quasi evaluation design. The descriptive analysis using 'with and without' data took over from that using 'before and after' data. The performance measures including pavement conditions and the effectiveness showed that PMS implementation improves pavement conditions. The improvements represent whether (i.e., efficacy) and how much (i.e., effectiveness) the PMS improves performance.

Regression analysis was also applied to this case study. The regression used the same pavement condition data as the descriptive analysis using with and without data, including the traffic weighted average pavement condition, AADT, and the use of PMS. The use of PMS as a dummy variable functioned to switch the regression model either from 'with case' or 'without case,' and then the model showed the efficacy and effectiveness of PMS implementation, which were explained by the improvement of the traffic weighted average condition. The improvement was the same point as that observed by the descriptive analysis because the regression model captured the same pavement condition changes with respect to AADT from year 2006 to 2019 as the descriptive analysis did.

The results of the descriptive analysis and regression analysis implied how much the PMS improve resource consumption (i.e., efficiency) because the 'with' case is constrained by the same amount of budget constraint of $55 million as the 'without' case. Since there were no available data to document the benefits and costs of PMS implementation, BCA was not conducted in this case study.

The two analysis methods used the two datasets to show the 3Es of PMS implementation. The data generated by VTrans was key. Creating the pavement condition as a result of M&R treatments produced by PMS is an easy task because PMS will create a list of treatments. Meanwhile, to create the results of M&R treatments based on a worst first strategy is a time consuming and complex task since required information, such as element data, do-nothing pavement condition values, treatments' costs and condition values, has to be imported from PMS and since all treatments have to be listed using the required data for 4015 road elements. If there is a function in the PMS to automatically experiment with a worst first strategy, it is then easy to observe the 3Es of PMS implementation.

The cases of 'with PMS' and 'without PMS' used the same AADT over 14 years. Strictly speaking, they may have different AADT from each other because pavement conditions affect vehicle speed and driving patterns. It is assumed that better pavement conditions increase vehicle speed and then induce additional traffic on an improved corridor. Also, the induced traffic may cause traffic congestion and thus decreases speed. Although it is difficult to predict future AADT with respect to pavement conditions based on the current conditions, it is worth conducting further study on this issue.

The results of the two analyses showed the differences in pavement conditions between ‘with’ and ‘without’ cases as the 3Es of PMS implementation. What causes the differences? One may be the appropriate M&R treatments selected by PMS to distribute pavement improvements to road elements where there is much traffic volume. The distribution of improvements contributes to reductions in agency costs[12], which are the benefits of PMS implementation. Another cause of the differences may be the difference in the treatment types considered between ‘with’ and ‘without’ cases. The ‘with case’ considers thin overlay, level and overlay, pulverize and overlay, and reconstruction, while the ‘without case’ does level and overlay only. Since the ‘without case’ is based on a worst first strategy that focuses on relatively heavily deteriorating pavements, thin overlay for light deteriorating pavements might be omitted. If deterioration in earlier stages is corrected by the thin overlay, the speed of deterioration is decelerated and then the lives of pavements increase and the M&R costs are saved. The budget savings can be applied for other treatments, and thus the ‘with case’ can achieve better pavement conditions than the ‘without case.’ Furthermore, although the level and overlay are effective to improve relatively light and mediocre deteriorating pavement, they are not effective for heavily deteriorating pavement. Therefore frequent level and overlay treatments are required to keep acceptable pavement conditions. Since the frequent treatments put pressure on the limited budget, required treatments might not be counted, and thus pavements further deteriorate in the ‘without case.’

Although this case study shows the applicability of the two methods, there are several future tasks in this study such as:

- Considering how an *ex post facto* evaluation using actual data can be incorporated into the analyses in the case in which an agency has incrementally implemented PMS over a number of years,
- Developing a method to identify various external influences on pavement management decisions and assess predicted pavement conditions while taking into account the influences,
- Assuring data and calculation qualities,
- Applying the same types of treatments to the ‘with’ and ‘without’ cases, and
- Considering agency, user, and external costs and PMS implementation costs in BCA to justify investment in PMS implementation.

Summary

This case study examined the benefits of PMS implementation using the two simulated datasets including pavement conditions with PMS and without PMS in VTrans’ road network over 14 years. For the analyses, the traffic weighted average pavement condition was used as an appropriate performance measure to include user and agency components. The two methods were employed and showed the following results:

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[12] The higher the traffic volume, the faster pavement deterioration is. Hence, investment in road elements where there is much traffic volume the early stages of deterioration can get large reduction in M&R costs. This may be called preventive maintenance. On the other hand, a worst first strategy focuses on pavement condition rather than traffic volume. As a result, there is much chance of pavements in earlier deterioration stage going to worse condition. The strategy may spend higher money than needed due to the failure to recognize the impacts of traffic volume.

- Descriptive analysis using with and without data, a quasi before and after data, showed that the mean of the traffic weighted average pavement condition with PMS is 10.1 points higher than that without PMS.
- The effectiveness between 'with' and 'without' cases is 19 percent.
- Regression analysis revealed traffic weighted average pavement condition increases 10.1 points if PMS is used.

The results show that PMS improves pavement conditions based on the differences between 'with' and 'without' cases, which represent the benefits of PMS implementation. The benefits demonstrate the efficacy, effectiveness, and efficiency of PMS implementation.

4.2. HERS-ST Case Study

This section describes a case study that evaluates the use of the HERS-ST, a highway investment and performance computer model, created by U.S. Department of Transportation and Federal Highway Administration. The objective of the HERS-ST case study is to recognize the benefits of HERS-ST in terms of the differences in performance measures including benefits to the agency, users, and externalities between a strategy based on HERS-ST and a worst first strategy.

HERS-ST

HERS-ST is a highway investment/performance computer model, which determines the impact of alternative highway investment levels and program structures (e.g., widening, resurfacing and reconstruction) on highway conditions, performance, and user costs. HERS-ST was developed by FHWA and is available at no cost (U.S. DOT and FHWA, 2006a). HERS-ST uses data from the Highway Performance Monitoring System (HPMS). HPMS is a national level highway information system, including data related to the extent, conditions, performance, use and operating characteristics of highways. The data are used for the biennial Condition and Performance Reports to Congress that analyzes highway system conditions, performance, and investment needs. The reports guide the Congress to establish authorization and appropriation legislation as well as to determine the scope and size of the Federal-aid Highway Program and the level of Federal highway taxation (U.S. DOT and FHWA, 2002b). As of August 2004, approximately 20 states either used HERS-ST or discussed with FHWA about HERS-ST implementation. An additional 22 states expressed interest in HERS-ST (U.S. DOT and FHWA, 2004).

HERS-ST provides three general evaluation scenarios as follows (U.S. DOT and FHWA, 2006a):

- What level of spending is required to achieve an economically optimal program structure that implements all economically worthwhile projects?
- What user cost/condition/performance level will result from a given spending level?
- What level of spending is required to achieve a certain level of user cost?

To obtain the results of the evaluation scenarios, HERS-ST follows the process depicted in Figure 41. Based on current conditions and traffic growth, HERS-ST predicts future pavement conditions and capacity deficiencies. From the condition and performance predictions, HERS-ST identifies deficiencies compared to deficiency criteria. Then, it identifies alternative treatments to correct each deficiency, and finally determines the most appropriate treatment that has a highest incremental benefit-cost ratio among potential treatments. This is the optimization of HERS-ST.

HERS-ST takes into account maintenance cost savings, travel-time savings, vehicle operating cost savings, safety benefits, pollution damage savings as benefits, and capital investments as costs (U.S. DOT and FHWA, 2005; 2006b).

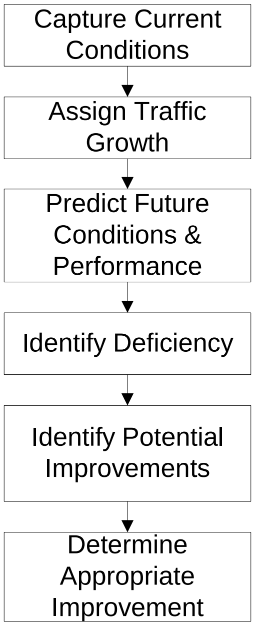

Figure 41. HERS-ST analytical procedures (U.S. DOT and FHWA, 2005)

Given the results of the evaluation scenarios, a transportation agency may be able to strategically program M&R treatments and assemble the budget needed for M&R from federal and local sources. Then, the agency may maintain the desired level of highway conditions, performance, and user impacts. Achieving desired levels of service reduces costs for agencies and highway users, and reduces the impact on the environment. From those points of view, HERS-ST is recognized as one asset management tool. Currently, 20 states are using or are in the process of implementing HERS-ST (U.S. DOT and FHWA, 2006c)

Analysis Method

This case study employs the three methods addressed in Section 3.1. HPMS data consisting of highway inventory and performance data from the State of New Mexico is included in the HERS-ST package[13]. This case study uses the data to demonstrate the efficacy of HERS-ST. Similar to the VTrans' case study, however, there is no data related to the costs of implementation of HERS-ST. Also, because the data capture highway inventory and performance in year 2001 only, it is impossible to track the trends of performances between before and after HERS-ST implementation. Like the Vermont case study, *ex ante* evaluation is conducted to accommodate the available data.

The condition of the highway network included as sample data in HERS-ST is summarized in Table 16, and graphically represented in Figure 42 and Figure 43. The network has 283 sections consisting of rural principal arterials, rural minor arterials, and urban principal arterials. Rural principal arterials are the largest class. Rural minor arterials are the second largest functional class. Although urban principal arterials have a number of sections, their lengths are

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[13] The package is downloadable via: http://www.fhwa.dot.gov/infrastructure/asstmgmt/hersrprep.htm.

lowest among the three classes. Their conditions are mostly good or better. The large portion of the network falls into fair, good, and very good conditions.

Settings

HPMS data do not include data before and after HERS-ST implementation but only data for the year 2001, although there are highway inventory and performance data. Hence, the same concept as the VTrans' case study, with and without data based on *ex ante* evaluation, is used in this case study. Using the data, two different scenarios are simulated based on HERS-ST (i.e., 'with HERS-ST') and a worst first strategy (i.e., 'without HERS-ST'). It is presumed that the difference between the two scenarios shows the benefits of HERS-ST implementation in pavement condition. The condition without HERS-ST may simulate the condition before HERS-ST implementation, while the condition with HERS-ST may simulate the condition after HERS-ST implementation.

Table 16. HIGHWAY NETWORK CONDITION IN HPMS DATA

Functional Class		Sections (Lengths: lane-miles)					
		Very Poor	Poor	Fair	Good	Very Good	Total
Rural	Principal Arterial	0 (0)	1 (1.32)	20 (106.10)	60 (543.18)	39 (487.65)	120 (1,138.25)
	Minor Arterial	0 (0)	1 (0.02)	9 (78.78)	18 (211.51)	4 (49.60)	32 (339.91)
Urban	Principal Arterial	2 (0.98)	15 (17.32)	41 (65.89)	60 (112.78)	13 (31.93)	131 (228.90)
Total		2 (0.98)	17 (18.66)	70 (250.77)	138 (867.47)	56 (569.18)	283 (1,707.06)

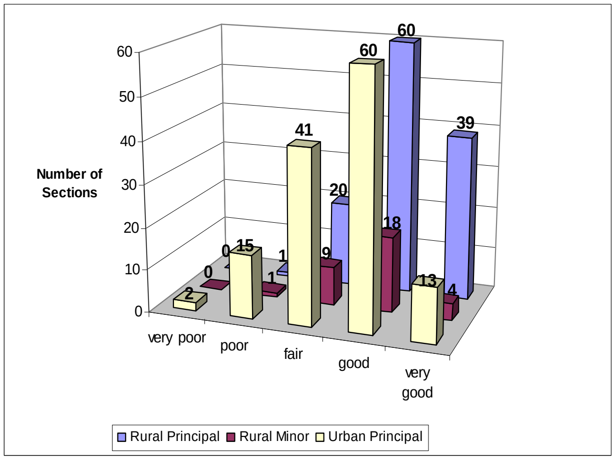

Figure 42. Sections of highway network in HPMS data

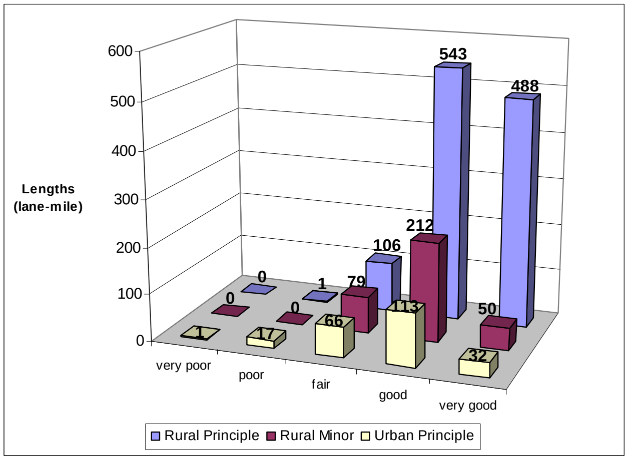

Figure 43. Lengths of highway network in HPMS data

The two strategies, worst first strategy and HERS-ST strategy, are used by HERS-ST per se to estimate future performance in the 'without HERS-ST case' and the 'with HERS-ST case,' respectively. The worst first strategy focuses on only sections that have deficiencies with respect to deficiency criteria listed in Table 17 and assigns treatments based on the criteria, while HERS-

ST strategy assigns the most appropriate treatment that has a highest benefit-cost ratio among potential treatments[14] for each highway section as recommended treatments.

Table 17. DEFICIENCY CRITERIA IN PSR

Treatments	Rural		Urban
	Principal Arterial	Minor Arterial	Principal Arterial
Resurfacing	$2.3 < PSR \leq 3.2$	$2 < PSR \leq 2.6$	$2.3 < PSR \leq 3.0$
Reconstruction	$PSR \leq 2.3$	$PSR \leq 2$	$PSR \leq 2.3$

The case 'without HERS-ST' is based on a worst first strategy developed using the ability to override treatment recommendations produced by HERS-ST with user-specified treatments that are included in State Improvements data[15]. Figure 44 depicts the concepts 'without HERS-ST case' and 'with HERS-ST case.' The line of HERS-ST recommended treatments represents the case 'with HERS-ST.' Since the case 'without HERS-ST' needs to avoid the influence of HERS-ST, user-specified treatments based on a worst first strategy should override the HERS-ST recommended treatments for the sections. The overriding is easily executed by the State Improvements data. The detail can be found in the HERS-ST user's guide.

Once the override is accomplished, we can perform the case 'without HERS-ST' by running HERS-ST analysis. The results of the analysis show system conditions, improvement statistics, and section conditions, based on those of the worst first strategy. Then they are compared to those of the case 'with HERS-ST' that are derived from another run of the HERS-ST analysis. The comparison shows the difference between the cases 'with HERS-ST' and 'without HERS-ST.'

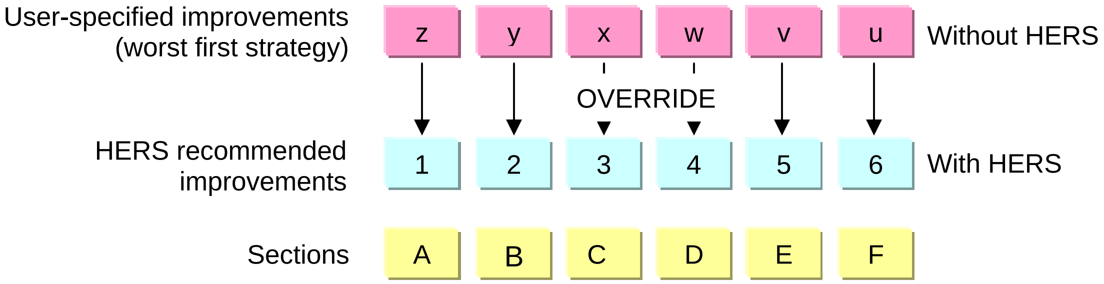

Figure 44. Concepts of without HERS-ST case and with HERS-ST case

Usually, transportation agencies program and update M&R treatments, for example, every five years based on current pavement conditions as a M&R program plan. Hence, this case study follows this practical manner. This case study considers a 10-year analysis period and divides the period into two 5-year periods: 2001-2005 and 2006-2010. Based on initial pavement

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[14] The potential treatments are do nothing, resurface, resurface with shoulder improvements, resurface with widen lanes, resurface with normal-cost lanes, resurface with high-cost lanes, reconstruction, reconstruction with widen lanes, reconstruction with normal-cost lanes, and reconstruction with high-cost lanes (U.S. DOT and FHWA, 2006a).

[15] By making State Improvement data override HERS-ST recommended treatments, a user can analyze the impacts of user-specified treatments compared with those of HERS-ST recommended treatments, with respect to the performance measures listed in APPENDIX E.

conditions in the two periods, two M&R treatment program plans are created and used for HERS-ST analysis.

Process

As Figure 45 demonstrates, this case study follows eight steps that fall into three components: without case, with case, and comparison. The details of the process are described in terms of the components.

Steps for Without Case

Step 1: Select sections. The first step selects highway sections in the HPMS data with respect to the deficiency criteria listed in Table 17 based on pavement conditions in 2001 to create user-specified treatments data as of 2001, which is described in Step 2. That is, sections having a Pavement Serviceability Rating (PSR) less than and equal to 3.2 on rural principal arterials, 2.6 on rural minor arterials, and 3.0 on urban principal arterials are selected. The criteria values in PSR are equivalent to default values in HERS-ST. The definition of PSR is described in **Table 18.** The number and length of selected sections are reported in Table 19 and Table 20. Eighty-eight sections are selected for Step 2. The reason why the sections having a good condition for user-specified treatments are not selected is because 'without case' based on a worst first strategy does not necessitate them. The worst first strategy focuses on sections that have deficiencies only. 'Without case' uses two treatments including resurfacing and reconstruction while 'with case' uses all available treatments such as resurfacing and improve shoulders, reconstruction with wider lanes, and so on, in HERS-ST.

Step 2: Make a list of M&R treatments. The second step makes a list of treatments based on a worst first strategy using the selected sections in Step 1. The worst first strategy prioritizes highway sections based on PSR and AADT. The worse the pavement condition, the faster a treatment is assigned to the section. Also, the more traffic volume a section has, the faster the section is assigned a treatment. The selected sections are rearranged based on ascending order with PSR and descending order with AADT. Then, two treatments, resurfacing and reconstruction, are assigned for the selected sections from 2001 to 2005 (i.e., the first 5-year period in the 10-year analysis period), based on the deficiency criteria listed in Table 21. Since a transportation agency tends to distribute budgets equally for M&R, the lengths for resurfacing and reconstruction are distributed equally over 5 years as much as possible (Table 21). Although treatments' years are specified here, HERS-ST considers that treatments are implemented in the middle of the funding period (FP)[16] to calculate benefits and costs in its output. Hence, the distribution of treatments is not critical at all. The funding period is equivalent to the 5-year period in this case study.

Step 3: Create the Set of State Improvements data. The third step creates the set of State Improvements data using the list of treatments based on a worst first strategy made in Step 2. We need to input year of treatment and treatment type for the sections selected in Step 1 in HERS-ST. At this time, override mode should be set to 'Yes.'

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[16] This is a simplified discrete time frame. User can determine the number and length of funding periods. The default setting is 20-year horizon divided into four 5-year funding periods (U.S. DOT and FHWA, 2006a).

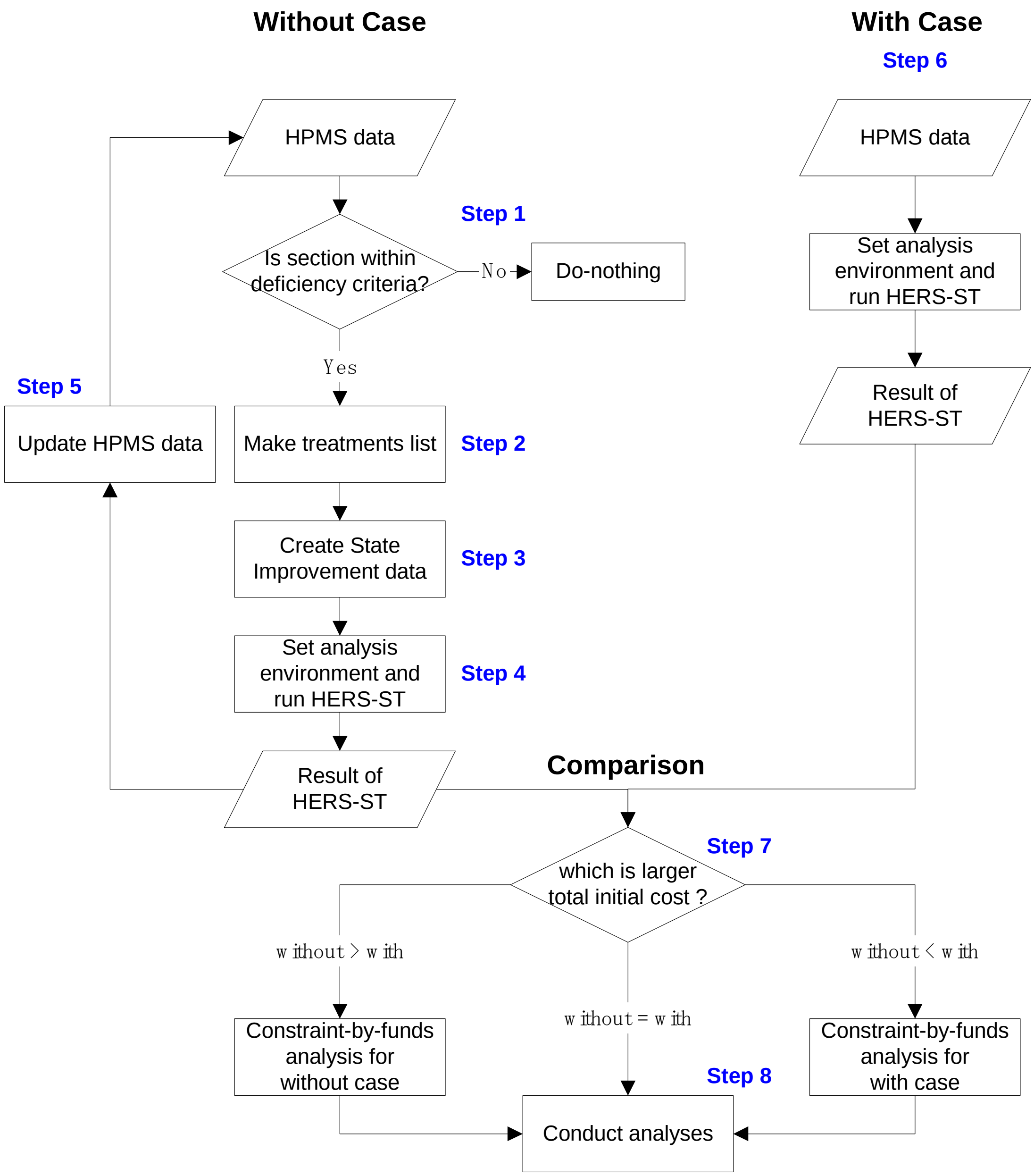


Figure 45. Flow diagram of process

Table 18. PAVEMENT CONDITION RATINGS

PSR and Verbal Rating	IRI Value -Rigid pavements (inch/mile)	Description
5.0	0	
Very Good		Only new (or nearly new) pavements are likely to be smooth enough and sufficiently free of cracks and patches to qualify for this category. All pavements constructed or resurfaced during the data year would normally be rated very good.
4.0	52	
Good		Pavements in this category; although not quite as smooth as those described above, give a first class ride and exhibit few, if any visible signs of surface deterioration. Flexible pavements may be beginning to show evidence of rutting and fine random cracks. Rigid pavements may be beginning to show evidence of slight surface deterioration, such as minor cracks and spalling.
3.0	119	
Fair		The riding qualities of pavements in this category are noticeably inferior to those of new pavements and may be barely tolerable for high speed traffic. Surface defects of flexible pavements may include rutting, map cracking, and extensive patching. Rigid pavements in this group may have a few joint failures, faulting and cracking, and some pumping.
2.0	213	
Poor		Pavements that have deteriorated to such an extent that they affect the speed of free-flow traffic. Flexible pavement may have large potholes and deep cracks. Distress includes ravelling, cracking, rutting, and occurs over 50 percent or more of the surface. Rigid pavement distress includes joint spalling, faulting, patching, cracking, scaling, and may include pumping and faulting.
1.0	374	
Very Poor		Pavements that are in an extremely deteriorated condition. The facility is passable only at reduced speeds and with considerable ride discomfort. Large potholes and deep cracks exist. Distress occurs over 75 percent or more of the surface.
0.068	999	

Source: U.S. DOT and FHWA, 2005

Table 19. NUMBERS OF SECTIONS AND SELECTED SECTIONS

Functional Class		Sections	Selected Sections	Breakdown of Selected Section	
				Resurfacing	Reconstruction
Rural	Principal Arterial	120	29 (24%)	25 (21%)	4 (3%)
	Minor Arterial	32	1 (3%)	0 (0%)	1 (3%)
Urban	Principal Arterial	131	58 (44%)	31 (24%)	27 (21%)
Total		283	88 (31%)	56 (20%)	32 (11%)

( ): Percentages of numbers of selected sections and treatments in selected sections with respect to numbers of total section.

Table 20. LENGTHS OF SECTIONS AND SELECTED SECTIONS (LANE-MILES)

Functional Class		Sections	Selected Sections	Breakdown of Selected Section	
				Resurfacing	Reconstruction
Rural	Principal Arterial	1138.25	155.64 (14%)	126.20 (11%)	29.44 (3%)
	Minor Arterial	339.91	0.02 (0%)	0 (0%)	0.02 (0%)
Urban	Principal Arterial	228.90	84.19 (37%)	53.72 (23%)	30.47 (13%)
Total		1707.06	239.85 (14%)	179.93 (11%)	59.92 (4%)

( ): Percentages of lengths of selected sections and treatments in selected sections with respect to lengths of total section.

Table 21. LENGTHS OF SELECTED SECTIONS FOR A WORST FIRST STRATEGY (LANE-MILES)

	2001	2002	2003	2004	2005	Total
Resurfacing	37.83	33.88	41.17	35.40	31.65	179.93
Reconstruction	11.58	12.07	6.96	15.56	13.76	59.92

Step 4: Set analysis environment and run HERS-ST analysis. The fourth step sets analysis environment for the first 5-year period, including discount rate, length of funding period, number of funding period, and run objective for ‘without case.’ The ‘without case’ sets the following: price reference year – 2004, discount rate – 4 %, length of funding period – 5 years, number of funding period – 1, and run objective – full engineering needs analysis. The full engineering needs analysis addresses the following questions (U.S. DOT and FHWA, 2006a):

- How much will it cost to correct all highway deficiencies for a funding period?
- What will the system’s condition and performance be?

Then this step runs HERS-ST analysis to analyze ‘without HERS-ST’ by overriding the State Improvements data created in Step 3 using the full engineering needs analysis.

Step 5: Update HPMS data. This fifth step updates the HPMS data such as year (i.e., change from 2001 to 2006), IRI, PSR, AADT, and right shoulder width, based on the result of the first 5-year HERS-ST analysis with the first set of State Improvement data. The updated HPMS data are used for the second 5-year period to obtain the result of HERS-ST analysis with the next set of State Improvement data. In doing so, the processes from Step 1 to Step 4 are iterated. After the updating process, Table 22 and Table 23, which depict numbers and lengths of selected sections for the second period, respectively, are determined. Using the selected sections, a list of M&R treatments identified in Table 24 is created and is used for the second State Improvements data. By overriding HERS-ST recommended treatments with the second State Improvement data, HERS-ST analysis provides the result of the second 5-year period. The result will be used later.

Table 22. NUMBERS OF SECTIONS AND SELECTED SECTIONS FOR SECOND PERIOD

Functional Class		Sections	Selected Sections	Breakdown of Selected Section	
				Resurfacing	Reconstruction
Rural	Principal Arterial	120	59 (49%)	50 (42%)	9 (8%)
	Minor Arterial	32	8 (25%)	7 (22%)	1 (3%)
Urban	Principal Arterial	131	41 (31%)	20 (15%)	21 (16%)
Total		283	108 (38%)	77 (27%)	31 (11%)

( ): Percentages of numbers of selected sections and treatments in selected sections with respect to numbers of total section.

Table 23. LENGTHS OF SECTIONS AND SELECTED SECTIONS FOR SECOND PERIOD (LANE-MILES)

Functional Class		Sections	Selected Sections	Breakdown of Selected Section	
				Resurfacing	Reconstruction
Rural	Principal Arterial	1138.25	559.16 (49%)	474.15 (42%)	85.01 (7%)
	Minor Arterial	339.91	111.07 (33%)	95.24 (28%)	15.83 (5%)
Urban	Principal Arterial	228.90	87.74 (38%)	51.64 (23%)	36.11 (16%)
Total		1707.06	757.97 (44%)	621.02 (36%)	136.94 (8%)

( ): Percentages of lengths of selected sections and treatments in selected sections with respect to lengths of total section.

Table 24. LENGTHS OF SELECTED SECTIONS FOR A WORST FIRST STRATEGY IN SECOND PERIOD (LANE-MILES)

	2006	2007	2008	2009	2010	Total
Resurfacing	122.46	124.63	117.96	134.72	121.26	621.02
Reconstruction	30.41	30.13	34.65	23.44	18.32	136.94

Steps for With Case

Step 6: Set analysis environment and run HERS-ST analysis. The sixth step sets analysis environment and run HERS-ST analysis for ‘with case.’ Since ‘with case’ utilizes HERS-ST optimization, the following are set: price reference year – 2004, discount rate – 4%, length of funding period – 5 years, number of funding period – 2, and run objective – minimum BCR analysis (i.e., BCR>1). The minimum BCR analysis addresses the following questions (U.S. DOT and FHWA, 2006a):

- What treatments exceed a specified minimum BCR?
- What level of investment would meet this BCR threshold?

- What will the condition and performance of the highway system be after investing at this level?

Although ‘without case’ conducts two HERS-ST analyses using the first and second State Improvement data, ‘with case’ needs one HERS-ST analysis only because HERS-ST automatically updates the second 5-year period based on the result of the first 5-year period. The result of the analysis for ‘with case’ is used in the next step.

Steps for Comparison

Step 7: Compare initial costs of with and without cases. The seventh step compares initial costs addressed in the results of HERS-ST analysis of ‘with case’ to total initial costs summing up initial costs in the first and second 5-year periods of ‘without cases.’ The objective of this comparison is to adjust the difference in the initial costs between the two cases because the equal amounts of initial costs are required to observe the difference in pavement conditions. There are three responses with respect to three conditions as Table 25 shows.

Table 25. RESPONSES IN COMPARISON OF INITIAL COSTS

Condition	Response
If without case > with case	For without case, use constraint-by-funds analysis with the same amount of funds as the initial cost for with case.
If without case = with case	Go to the next step.
If without case < with case	For with case, use constraint-by-funds analysis with the same amount of funds as the initial cost for without case.

The constraint-by-funds analysis addresses the following questions (U.S. DOT and FHWA, 2006a):

- How many treatments can be implemented at the specified fund level?
- What level of system condition and performance can be obtained when the treatments are implemented?

The comparison in this case study showed that the initial cost of ‘without case’ is larger than that of ‘with case.’ Because the initial cost in the first 5-year period falls within the initial cost in the first FP of ‘with case,’ the initial cost in the second 5-year period of ‘without case’ was adjusted by the constraint-by-funds. Due to the constraint, the output of HERS-ST shows different treatment selection (i.e., resurfacing and reconstruction) from Table 22 and Table 23 in Step 5. If the initial cost in the first 5-year period of ‘without case’ is larger than that in the first FP of ‘with case,’ the constraint-by-funds analysis needs to be applied for the first HERS-ST analysis for the first 5-year period of ‘without case.’

Step 8: Conduct analyses. The eighth and last step is to conduct analyses including the three methods (i.e., descriptive analysis using with and without data, regression analysis, and benefit-cost analysis) addressed in the following subsections. These methods compare the results of HERS-ST analyses of ‘with’ and ‘without’ cases.

Benefit Quantification

For quantifying the benefits of HERS-ST implementation, the methods identified in Section 3.1 are used to articulate the 3Es of HERS-ST implementation as follows:

Descriptive Analysis Using Before and After (With and Without) Data

This case study also uses ‘with and without data’ instead of ‘before and after data’ due to lack of actual observed data related to highway inventories and performance before and after HERS-ST implementation. Since HERS-ST provides various performance measures listed in APPENDIX E, the analysis can demonstrate differences in the measures between ‘with’ and ‘without’ cases. While HERS-ST produces an average pavement condition for each funding period for each element, the average network performance is used for the analysis, as it is the network that is of discount. This result shows whether there are the efficacy and effectiveness derived from HERS-ST implementation. Also, the comparison of the ratios of improvements of pavement conditions to the costs for M&R treatments between ‘with’ and ‘without’ cases can identify the efficiency.

Using the results of HERS-ST analyses of ‘with’ and ‘without’ cases, the two kinds of pavement performance measures are calculated to conduct the descriptive analysis using with and without data as follows:

- Traffic weighted average pavement condition by year (Scale: 0-5)

$$\text{Traffic Weighted Average Pavement Condition} = \frac{\sum_{i=1}^{283}(PSR_i \times AADT_i \times Length_i)}{\sum_{i=1}^{283}(AADT_i \times Length_i)} \qquad (8.9)$$

where:

PSR : Pavement Serviceability Rating
AADT : Annual average daily traffic
Length : Length of road elements in mile
i : Road element’s number

- Percent travel by condition by year
  e.g., for Very Poor

$$\text{Percent travel by Very Poor} = \frac{\sum_{j=J}^{283}(Length_j \times AADT_j)}{\sum_{i=1}^{283}(Length_i \times AADT_i)} \times 100,\ \forall j = VeryPoor \qquad (8.10)$$

Also, there are poor, fair, good, and very good conditions besides very poor.

In addition, the effectiveness used in VTrans’ case study is demonstrated in the descriptive analysis as one performance measure. Since there are only three data points in each section, that is, initial period, FP1, and FP2, effectiveness is shown by the net area under the curve (the area under the curve with HERS-ST minus the area under the curve without HERS-ST) connecting between the two points as Figure 46 depicts. To obtain the effectiveness, the following equation is used:

$$\text{Effectiveness} = \sum_{i=1}^{283}\sum_{t=2001}^{2010}\left\{(PSR_{i,t}^{w/HERS} - PSR_{i,t}^{w/oHERS}) \times AADT_{i,t} \times Length_i\right\} \qquad (8.11)$$

where:

PSR : Pavement Serviceability Rating

AADT	:	Annual average daily traffic
Length	:	Length of sections in mile
i	:	Sections' number (283 sections)
t	:	Year (2001, 2005, and 2010)

Regression Analysis

The regression analysis model used for the VTrans' case study is also applied for this case study to observe the efficacy of HERS-ST in the network level. Also, the degree of the coefficient shows effectiveness and efficiency (since 'with' and 'without' cases have almost the same amounts of a budget constraint) of HERS-ST implementation. The candidate models are as follows:

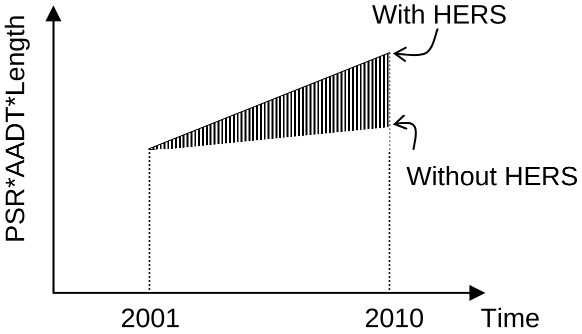


Figure 46. Schematic illustration of effectiveness in HERS-ST case

$$\text{Traffic Weighted Average Pavement Condition}_t = f(\text{AADT}_t, \text{HERS}_t) \quad (8.12)$$

where:

For t =2001, 2005, and 2010

Traffic Weighted Average Pavement Condition $_t$	:	Traffic weighted average pavement condition (e.g., PSR) in year t
AADT $_t$	:	Total annual average daily traffic in year t
HERS $_t$	:	Use of HERS-ST in year t (dummy variable: 1- yes; 0- no)

The initial condition and the results of FP 1 and FP 2 from both 'with' and 'without' cases listed in Table 26 are used to build the regression model.

Table 26. DATA FOR REGRESSION ANALYSIS

Year	TWAPC	AADT	HERS-ST
2001 (initial)	3.605	2023345	1
2001 (initial)	3.605	2023345	0
2005	3.740	2253153	1
2005	3.103	2220832	0
2010	3.653	2457950	1
2010	3.400	2431882	0

Benefit-Cost Analysis

To quantify the benefits of HERS-ST implementation in monetary value, BCA is used and needs the benefits and negative benefits (i.e., costs) addressed in Table 5. Since HERS-ST addresses total initial cost for M&R and average benefit-cost ratio (BCR) for each funding period, we can obtain total monetary benefits from multiplying the total initial costs by the BCRs in two funding periods. If we calculate the total net benefits (i.e., the total benefits minus total initial costs) for 'with' and 'without' cases and then compare each other, we can show the efficacy and effectiveness of HERS-ST implementation. Since the total benefits and total initial costs for both cases are available at this time, we also can calculate their BCRs and then articulate the efficiency of HERS-ST implementation based on the degree of BCRs.

Investment Justification

Again, BCA is used to justify investment in HERS-ST implementation. Since there are no available data related to HERS-ST implementation costs, it is impossible to conduct both the net present value method estimated by the difference between total discounted costs and benefits and the BCR method showing the ratio of benefits over costs. However, if the grand total net benefits produced by HERS-ST implementation (i.e., the difference in the total net benefits between 'with' and 'without' cases) is calculated by the process above, we can provide information for discussion of whether the benefits exceed HERS-ST implementation costs. For example, if an agency spends less amount of HERS-ST implementation costs than the benefits derived from the difference in the total benefits between 'with case' and 'without case' until 2010, it can be concluded that the agency can get a return of investment in HERS-ST implementation. The relationship can be shown by the following expressions:

$$\begin{aligned}&((\text{Total Net Benefits with HERS-ST}) - (\text{Total Net Benefits without HERS-ST}))\\ &\qquad - (\text{HERS Implementation Costs}) \geq 0 \end{aligned} \tag{8.13}$$

or

$$\frac{((Total\_Net\_Benefits\_withHERS) - (Total\_Net\_Benefits\_withoutHERS))}{(HERS\_implemnetationCosts)} \geq 1.0 \tag{8.14}$$

The relationships expressed by equations (8.13) and (8.14) are similar to the net present value method and the benefit-cost ratio method, respectively. If there is a remainder derived from equation (8.13), it shows residual benefits exceeding implementation costs expressed by monetary value of HERS-ST implementation. This analysis is from the perspective of net social welfare but a similar analysis can be conducted from the perspective of the agency.

As HERS-ST has an elaborate system of models for both user and agency costs, HERS-ST provides a rich set of data for evaluation. While this data is panel data – section data over several years – it is used as aggregate data at the network level to estimate the value of using HERS. This is consistent with the modeling strategy embedded with HERS which was developed for use at the network level.

Analysis Results

Following the analysis methods described in Section 3.1, the benefits of using HERS-ST are assessed using aggregate data as follows:

Benefit Quantification

Using the three analysis methods, the benefits of HERS-ST implementation are quantified in terms of the 3Es.

Descriptive Analysis Using With and Without Data

HERS-ST runs HERS-ST analysis for 'with case' (i.e., running with HPMS data using the minimum BCR analysis) and 'without case' (i.e., running with HPMS data and the State Improvements data using the full engineering needs analysis). After running HERS-ST, the difference in the initial costs between 'with' and 'without' cases was recognized. Hence, the initial cost of 'without case' was adjusted to be equal to that of 'with case' using the constraint-by-funds analysis as shown in Table 27. Since the difference between the two cases is 0.6 percent (= (779,261-774,955)/774,955), we assume that 'with' and 'without' cases have the same levels of amounts of initial cost for M&R treatments.

Table 27. INITIAL COSTS OF WITH AND WITHOUT HERS-ST CASES

Case	Initial Costs ($Thousands)		
	FP 1	FP 2	Total
With HERS-ST	553,170	226,091	779,261
Without HERS-ST	234,350	540,585	774,955

Table 28 shows the mean of the traffic weighted average pavement condition from 2001 to 2010. For all functional classes, the mean with HERS-ST is 0.30 points (=3.67-3.37) higher than that without HERS-ST. The increase is equivalent to 9 percent (=0.30/3.37) of the traffic weighted average pavement condition without HERS-ST. Among the three functional classes, rural principal arterials show the highest point increase at 0.35, while rural minor arterials show the lowest point increase at 0.09. Hence, it is expected that HERS-ST improve pavement conditions of all functional classes over 10 years.

Table 28. MEANS OF TRAFFIC WEIGHTED AVERAGE PAVEMNET CONDITION OVER 10 YEARS

Functional Class		With HERS-ST	Without HERS-ST	Difference (w/-w/o)
All		3.67	3.37	0.30
Rural	Principal Arterial	3.82	3.46	0.35
	Minor Arterial	3.15	3.05	0.09
Urban	Principal Arterial	3.56	3.30	0.26

The increases in the traffic weighted average pavement condition identified in Table 28 are graphically demonstrated in Figure 47 to Figure 50. Overall, 'with case' shows relatively stable, good pavement condition with respect to pavement condition ratings listed in

Table 18, compared to 'without case' over 10 years. Obviously, there are differences between with and without HERS-ST in the rural and urban principal arterials where there are higher AADTs except for the rural minor arterials where there is lowest AADT (see Figure 59 and Figure 60). It is assumed that HERS-ST prioritizes treatments for the arterials having higher AADT because it is effective to maximize benefits in agency, user, and externality, using a limited budget. Thus, those arterials expect to have larger differences in pavement condition between with and without HERS-ST than the rural minor arterials do.

Figure 51 to Figure 54 and Figure 55 to Figure 58 depict percent travel by pavement condition with HERS-ST and without HERS-ST, respectively. Significant differences are: 1) with HERS-ST has higher percentage of very good condition and lower percentage of fair conditions than without HERS-ST in 2005; 2) with HERS-ST has higher percentage of good conditions and lower percentage of fair conditions than without HERS-ST in 2010; and 3) with HERS-ST has lower percentage of poor and very poor conditions in 2005 and 2010. Table 29 shows the mean of percent travel by pavement condition over 10 years. Although it does not provide temporal information, the three differences addressed above can be observed.

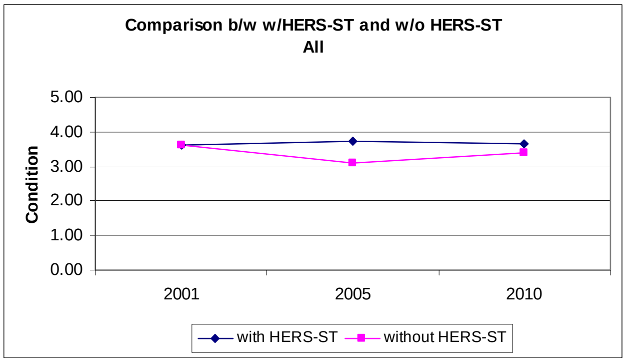


Figure 47. Comparison of traffic weighted average pavement conditions (All)

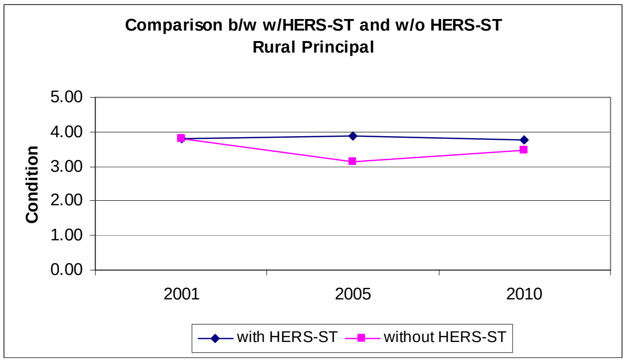


Figure 48. Comparison of traffic weighted average pavement conditions (Rural Principal)

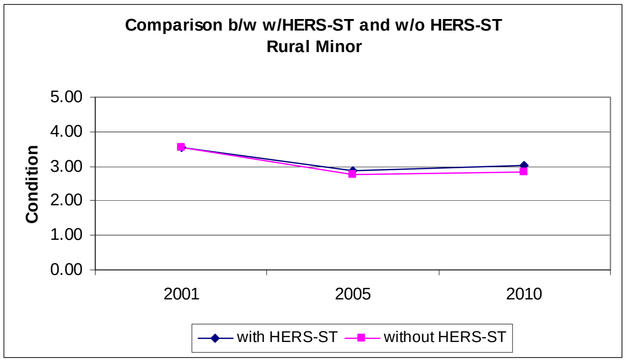


Figure 49. Comparison of traffic weighted average pavement conditions (Rural Minor)

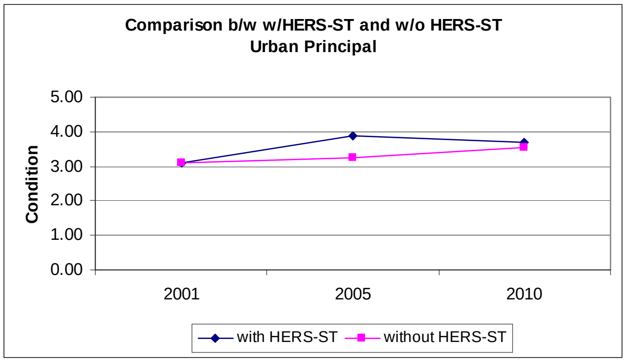
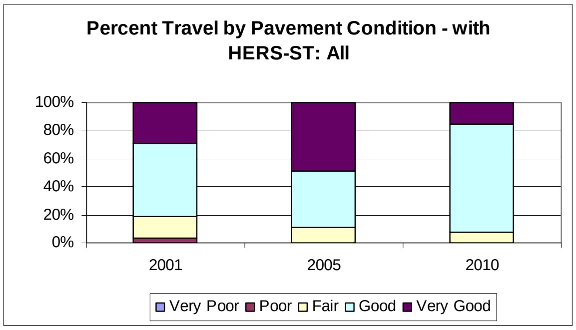


Figure 50. Comparison of traffic weighted average pavement conditions (Urban Principal)

With HERS-ST



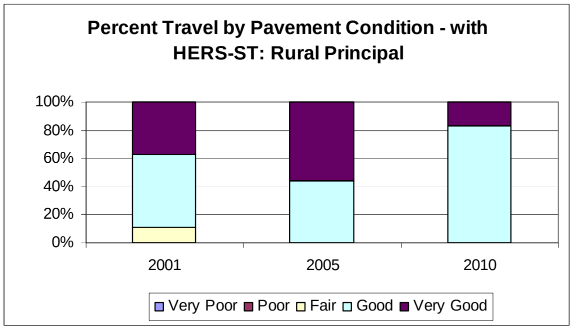
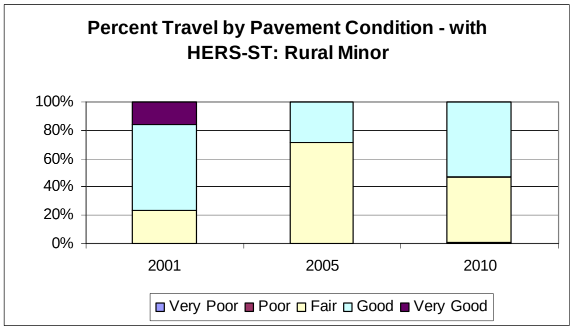


Figure 51. Percent travel by condition with HERS-ST (All)

Figure 52. Percent by travel by condition with HERS-ST (Rural Principal)



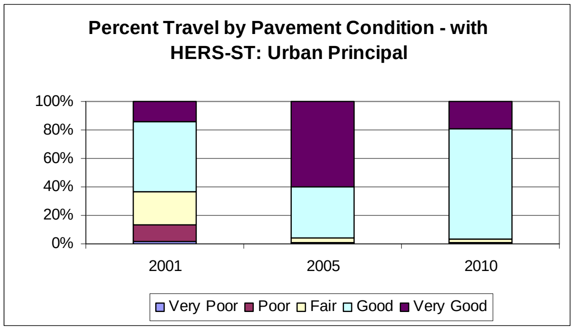
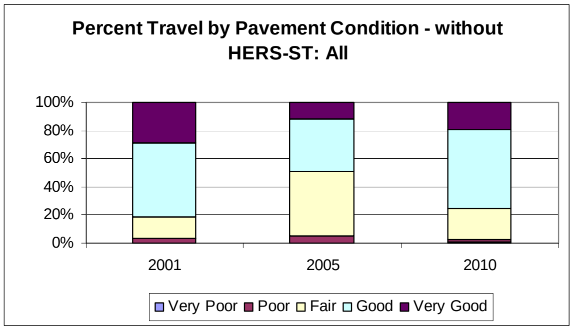


Figure 53. Percent travel by condition with HERS-ST (Rural Minor)

Figure 54. Percent travel by condition with HERS-ST (Urban Principal)

Without HERS-ST (worst first strategy)



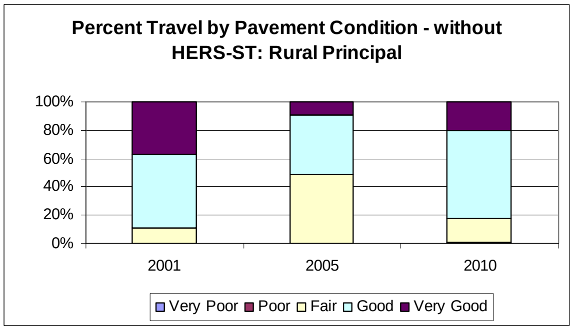
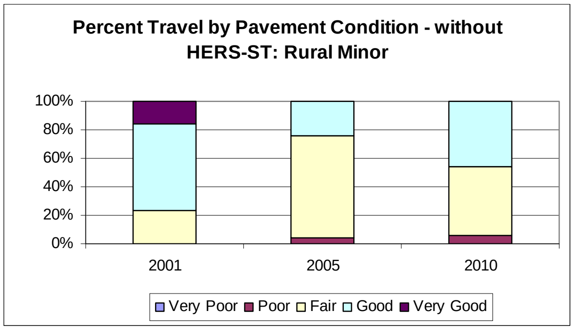


Figure 55. Percent travel by condition without HERS-ST (All)

Figure 56. Percent travel by condition without HERS-ST (Rural Principal)



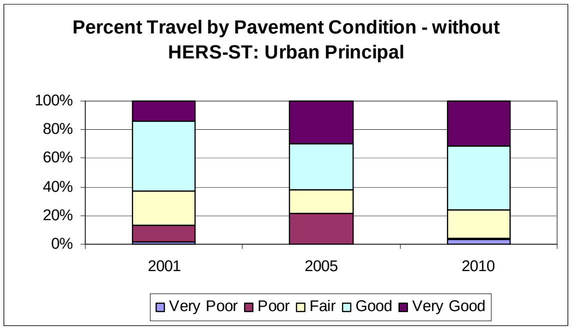


Figure 57. Percent travel by condition without HERS-ST (Rural Minor)

Figure 58. Percent travel by condition without HERS-ST (Urban Principal)

Table 29. MEAN OF PERCENT TRAVEL BY PAVEMENT CONDITION OVER 10 YEARS

Functional Class		With HERS-ST					Without HERS-ST				
		Very Poor	Poor	Fair	Good	Very Good	Very Poor	Poor	Fair	Good	Very Good
All		0%	1%	11%	57%	31%	0%	3%	28%	49%	20%
Rural	Principal	0%	0%	4%	60%	37%	0%	1%	25%	52%	22%
	Minor	0%	0%	47%	47%	5%	0%	3%	48%	43%	5%
Urban	Principal	1%	4%	10%	54%	31%	2%	11%	20%	42%	25%

Figure 59 and Figure 60 show AADTs of with HERS-ST and without HERS-ST, respectively. The rural and urban principal arterials occupy the majority of AADT, 96 percent, in both ‘with’ and ‘without’ cases over 10 years. Both cases have about 20 percent growth from 2001 to 2010. The urban principal arterials would experience the most congested traffic conditions and the most damaged structural conditions because of the lowest lane-miles and the highest AADT among the three functional classes. Comparing both cases with each other, AADT with HERS-ST is 1 percent larger than that without HERS-ST in all functional classes. The increase, that is, induced traffic, may be caused by smoother surfaces and wider lanes improved by HERS-ST recommendations. However, AADT difference of the rural minor arterials between with and without HERS-ST shows no increase from 2001 to 2005 and a 1 percent decrease from 2005 to 2010.

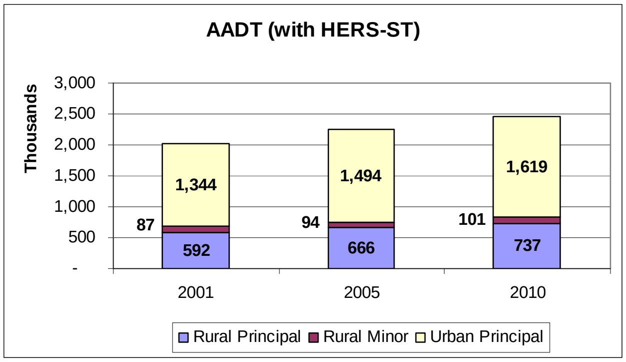


Figure 59. AADT of with HERS-ST case

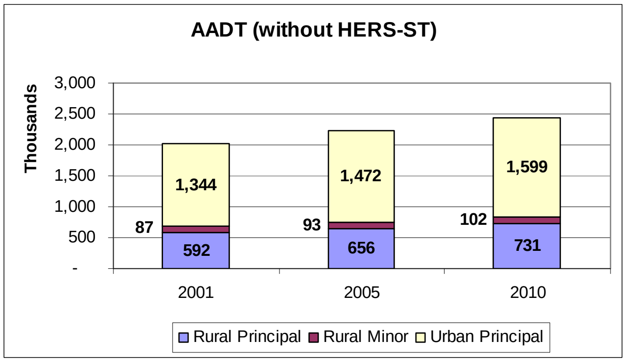


Figure 60. AADT of without HERS-ST case

Figure 61 to Figure 68 depict treatments of the first five-year period, FP 1, and the second five-year period, FP 2, in terms of number of sections and lane-miles 'with' and 'without' cases. The information regarding the treatment types is available in the section condition outputs of HERS-ST. 'With case' employs four treatment types: resurface, resurface and improve shoulders, resurface and add high-cost lanes, and pavement reconstruction, while 'without case' employs three treatment types: resurface, resurface and improve shoulders, and pavement reconstruction. Although 'without case' assigned two types, resurface and pavement reconstruction using the State Improvement data, HERS-ST automatically employed the option of resurface and improve shoulders for 7 sections (34 lane-miles) in FP 1 and 8 sections (88 lane-miles) in FP 2. Hence, 'without case' does not reflect the worst first strategy determined completely.

If focusing on resurfacing, 'with case' has larger sections and lane-miles in FP 1 than in FP 2. Because HERS-ST recommends a resurface treatment based on pavement condition at the end of the funding periods (U.S. DOT and FHWA, 2005), 'with case' counts larger sections and lane-miles than 'without case,' a worst first strategy, which considers pavement condition at the beginning of the funding periods. During the first five-year period, FP 1, a number of sections may deteriorate and thus will be selected by HERS-ST as candidates for resurfacing in FP 1. Conversely, 'without case' has larger sections and lane-miles in FP 2 than in FP 1, because 'without case,' relying on a worst first strategy, looks at the pavement condition at the beginning of the funding periods. Although some sections are beyond the criteria for resurfacing listed in Table 17 at the beginning of FP 1, the sections will deteriorate during FP 1 and they eventually need to be resurfaced in FP 2.

Concerning pavement reconstruction, 'with case' has fewer sections and lane-miles than 'without case.' This may be caused by HERS-ST's selection criteria that take into account pavement conditions, surface type, and widening (U.S. DOT and FHWA, 2005), different from a worst first strategy focusing on pavement conditions only. In other words, 'with case' uses stricter selection criteria.

With HERS-ST

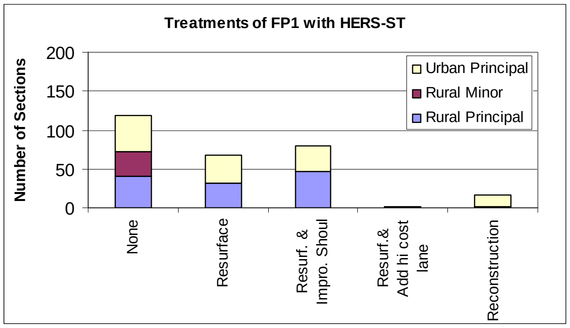


Figure 61. Treatments of FP1 with HERS-ST (Number of Sections)

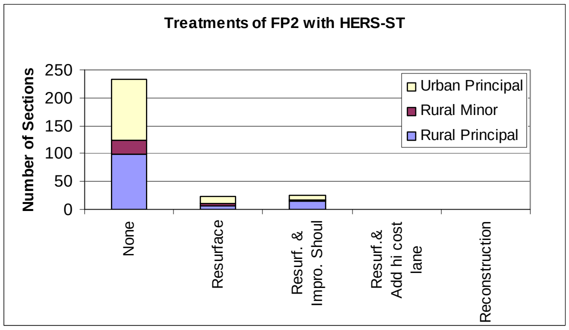


Figure 62. Treatments of FP2 with HERS-ST (Number of Sections)

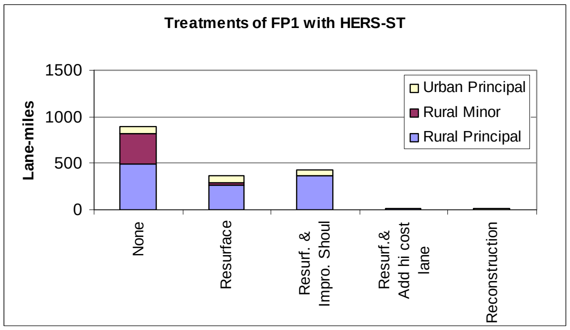


Figure 63. Treatments of FP1 with HERS-ST (Lane-miles)

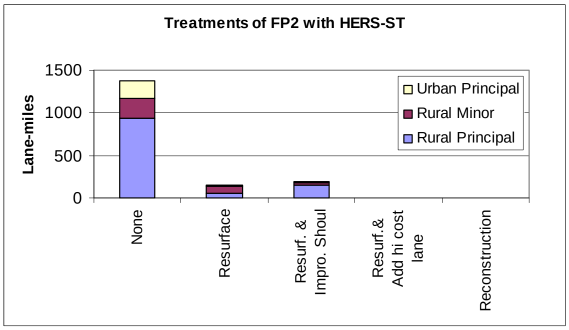


Figure 64. Treatments of FP2 with HERS-ST (Lane-miles)

Without HERS-ST (worst first strategy)

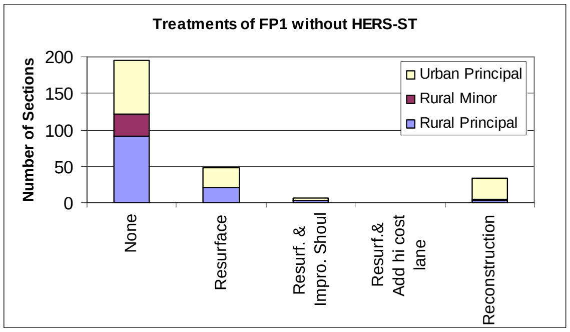


Figure 65. Treatments of FP1 without HERS-ST (Number of Sections)

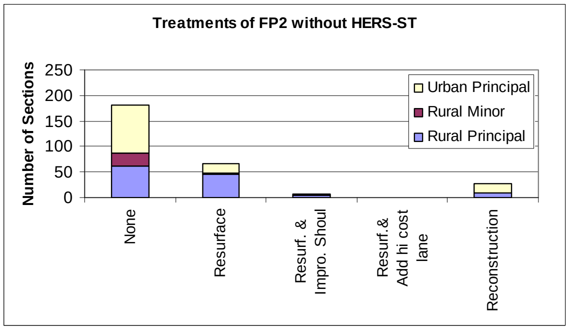


Figure 66. Treatments of FP2 without HERS-ST (Number of Sections)

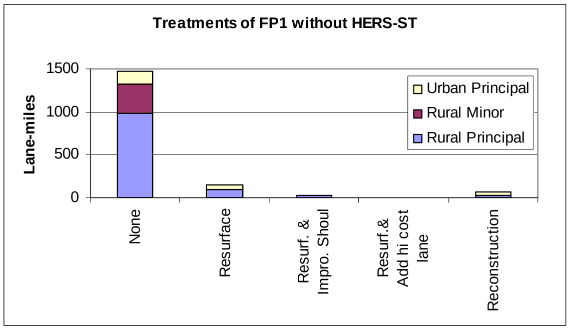


Figure 67. Treatments of FP1 without HERS-ST (Lane-miles)

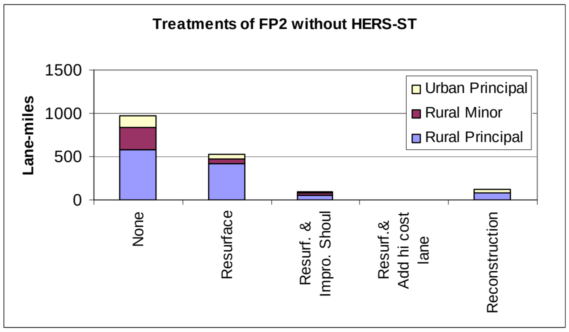


Figure 68. Treatments of FP2 without HERS-ST (Lane-miles)

Table 30 shows various performance measures of the cases with and without HERS-ST, in terms of FP 1 (2001-2005), FP 2 (2006-2010), and overall. The followings are found:

- Total initial cost for selected treatments of 'with case' is 0.6 percent larger than that of 'without case.'
- Total benefits in the last year of FP1 and FP2 of 'with case' are higher than those of 'without case.' Maintenance cost savings and safety benefits contribute to the higher benefits of 'with case.' 'With case' may be more efficient to achieve good and acceptable highway performances in terms of pavement condition and safety.
- 'With case' shows worse results in savings in travel-time and vehicle operating cost compared to 'without case' in the last year of FP 1. This result may be caused by induced traffic due to larger improved sections in 'with case' as VMT of improved sections shows.
- 'With case' results in less pollution damage than 'without case' in the last year of FP 1, but higher in the last year of FP 2.

Table 30. WITH AND WITHOUT PERFORMANCE MEASURES

Performance Measure	With HERS-ST			Without HERS-ST		
	FP 1	FP 2	Overall	FP 1	FP 2	Overall
Total Initial Cost ($thousand)[a]	553170	226091	779261	234350	540585	774935
Lane-Miles Improved[a]	1745	900	2645	508	1667	2175
Average BCR[a]	8.635	5.963	7.860	3.901	5.881	n.a.
Miles Improved[a]	594	341	935	177	613	790
Lane-Miles Added[a]	12	2	14	0	0	0
Capital Requirements by IBCR Range[b]	553170	226091	n.a.	198401	531431	n.a.
Sample Sections by IBCR Range[b]	164	49	n.a.	72	100	n.a.
Miles Improved by IBCR Range[b]	594	341	n.a.	167	610	n.a.
Travel-Time Benefits by IBCR Range[b]	6.1	11.8	n.a.	9.1	32	n.a.
Total Benefits ($thousand)[b] Excluding pollution damage savings	451333	122316	n.a.	111236	454617	n.a.
Maintenance Cost Savings ($thousand)[b]	323266	72843	n.a.	60839	254716	n.a.
User Benefits ($thousand)[b]	128067	49473	n.a.	50396	199900	n.a.
Travel-Time Savings ($thousand)[b]	4952	5435	n.a.	2803	39401	n.a.
Operating Cost Savings ($thousand)[b]	111447	40686	n.a.	46368	153257	n.a.
Safety Benefits ($thousand)[b]	11667	3352	n.a.	1223	7241	n.a.
Crashes Avoided ($thousand)[b]	10	-2	n.a.	-32	-56	n.a.
Injuries Avoided[b]	20	0	n.a.	-12	-22	n.a.
Lives Saved[b]	1	0	n.a.	0	0	n.a.
VMT of Improved Sections[b]	1254	463	n.a.	404	1143	n.a.
Pollution Damage Savings ($thousand)[b]	-1257	-1762	n.a.	-485	-3742	n.a.

Notes: Costs are based on 2004 dollars.

[a] These represent values during each funding period.

[b] These represent values during the last year of each funding period.

Table 31 shows the system conditions with HERS-ST and without HERS-ST, at the initial (2001), the end of FP 1 (2005), and the end of FP 2 (2010). Given the results the followings are observed:

- Since ‘with case’ implements the treatment of resurface and add high-cost lanes, lane-miles increase both in FP 1 and in FP 2.

- In the pavement conditions expressed by average PSR and IRI, ‘with case’ is better (higher IRI, lower PSR) than ‘without case.’ To keep the same level of pavement condition as the initial condition, ‘without case’ needs more investment.
- ‘With case’ has higher average speed and lower delay than ‘without case’ does.
- In safety aspects, ‘with case’ has lower costs and rates in crash, injury, and fatality, possibly, because of the different treatment, add high-cost lanes.
- In total user costs consisting of travel time costs, vehicle operating costs, and safety costs, ‘with case’ has a lower value than ‘without case.’
- ‘With case’ needs lower maintenance costs than ‘without case’ although ‘with case’ can achieve better pavement condition.
- The emission costs of ‘with case’ significantly decrease over 10 years compared to ‘without case.’ Emission costs decrease as average vehicle speed increases until a certain speed (i.e., four-tire vehicle: 40 mph, trucks: 35 mph). Over this speed limit, air pollution costs increase as the speed increases[17]. Because better pavement condition leads to higher average vehicle speed, this situation may closely link with the average vehicle speed. However, ‘with’ and ‘without’ cases show the almost same average vehicle speeds of rural principal arterials (about 60 mph), rural minor arterials (about 55 mph), and urban principal arterials (about 42 mph) in FP1 and FP 2. Hence, it is needed to verify the accuracy of the result in the future.

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[17] Table 5-32 in U.S. DOT and FHWA, 2005

Table 31. WITH AND WITHOUT SYSTEM CONDITIONS

System Condition		Initial	With		Without	
			FP 1	FP 2	FP 1	FP 2
Mile		1621.4	1621.4	1621.4	1621.4	1621.4
Lane-Miles		4307.7	4319.8	4321.9	4307.7	4307.7
Average PSR		3.576	3.656	3.583	3.085	3.326
Average IRI		93.5	86.0	90.1	134.2	114
Average Speed – Overall	MPH	55.600	55.585	55.537	55.400	55.366
Delay – Zero Volume	Hours/1000VMT	0.095	0.094	0.092	0.096	0.092
Delay – Incident	Hours/1000VMT	0.051	0.053	0.059	0.057	0.061
Delay – Other	Hours/1000VMT	0.420	0.433	0.468	0.461	0.511
Delay – Total	Hours/1000VMT	0.566	0.580	0.619	0.614	0.664
VMT – 4 Tire Vehicle	Millions	1669	1851	2031	1819	2023
VMT – Single Unit Trucks	Millions	184	204	224	201	224
VMT – Combination Trucks	Millions	261	290	320	286	320
VMT – All	Millions	2115	2346	2576	2307	2568
VHT[a] – 4 Tire	Millions	30	33	37	33	37
VHT – Single Unit Trucks	Millions	3	3	3	3	3
VHT – Combination Trucks	Millions	4	4	5	4	5
VHT – All	Millions	38	42	46	41	46
Travel Time Costs – 4 Tire Vehicles	$/1000VMT	365	365	365	366	366
Travel Time Costs – Trucks	$/1000VMT	531	531	533	533	535
Travel Time Costs – All	$/1000VMT	400	400	401	401	402
Operating Costs – 4-Tire Vehicles	$/1000VMT	268	265	266	288	277
Operating Costs – Trucks	$/1000VMT	608	613	612	657	633
Operating Costs – All	$/1000VMT	340	338	339	366	352
Crash Costs	$/1000VMT	109	105	104	109	107
Total User Costs	$/1000VMT	850	844	844	878	862

System Condition		Initial	With		Without	
Crash Rate	/100 million VMT	149.7	145.7	144.6	150.1	147.3
Injury Rate	/100 million VMT	79.1	76.5	75.8	79.2	77.5
Fatality Rate	/100 million VMT	1.57	1.49	1.48	1.57	1.53
Maintenance Costs	$/1000 mile	215792	128345	105660	290192	152946
Emissions Costs	$/1000VMT	28.744	18.531	12.144	18.512	18.502
BCR of Last Improvement		n.a.	1.014	1.163	0	1.199

Notes: Costs are based on 2004 dollars.

[a] Vehicle hours of travel-time

The effectiveness was analyzed using equation (8.11). Figure 69 shows the products of PSR, AADT, and length of 'with' and 'without' cases. As demonstrated, the value of 'with case' in 2005 and 2010 are higher than that of 'without case.' Hence, the effectiveness of HERS-ST implementation is 2,750,330, about 10% increase from 'without case.'

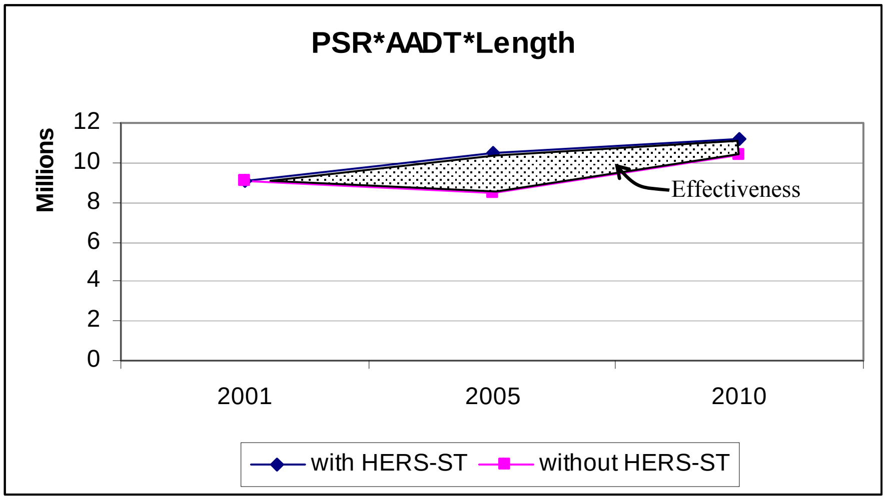

Figure 69. Products of PSR, AADT, lane, and length of with HERS-ST case and without HERS-ST case

Regression Analysis

Regression analysis employed the traffic weighted average pavement condition to capture the 3Es of HERS-ST implementation in the network level based on model (8.12). Figure 70 depicts the relationship between the traffic weighted average pavement condition and AADT, using the data described in Table 26. The following model intends to graphically show the relationship similar to the result observed in the descriptive analysis, although there is a difference in whether the x-axis uses AADT or time.

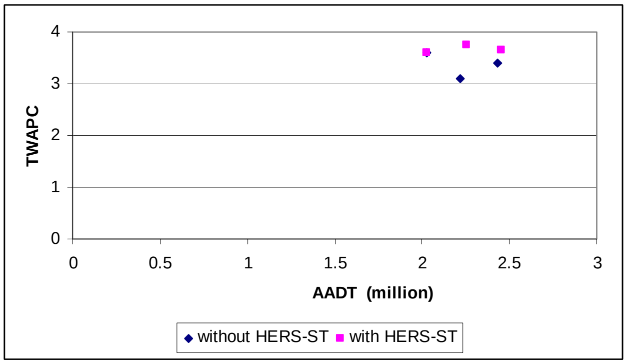

Figure 70. Relationship between traffic weighted average pavement condition and AADT

Let $TWAPSR_n$ be the traffic weighted average PSR in funding period n, $AADT_n$ be the total annual average daily traffic in all sections in funding period n, and $HERS_n$ be the use of HERS-ST in funding period n. The model to be estimated is:

$$TWAPSR_n = \beta_0 + \beta_1 AADT_n + \delta_{1n} HERS_n + \varepsilon_n \qquad (8.15)$$

where:

β_0, β_1, and δ_{1n} : Parameters
ε_n : Error term associated with the n th traffic weighted average PSR
δ_{1n} : Coefficient for the dummy variable
e.g., δ_{1n} is equal to 1 if HERS-ST is used in funding period n and equal to 0 otherwise

With only 6 observations, they results are not meaningful. The results are not included here but are available in Mizusawa (2007). Although model (8.15) failed to capture the efficacy of HERS-ST in the network level in statistical perspective due to the limited number of observations, we can intuitively expect that the use of HERS-ST improve pavement condition by observing Figure 70.

Benefit-Cost Analysis

Using the total initial costs for M&R and average BCRs of 'with' and 'without' cases listed in Table 30, total benefits in terms of FP 1, FP2, and total initial costs are summarized in Table 32. Because HERS-ST analysis outputs show the benefits in the last year in funding periods, the total benefits are obtained by multiplying the initial costs by the average BCRs. There is no information about how the total benefits are broken down into agency, user, and external benefits. Hence, Table 32 lists the total benefits only.

Given the result, it is obvious that 'with case' is more efficient in keeping good pavement conditions in the network level because 'with case' can obtain higher benefits, including agency, user, and external benefits, using almost the same total initial cost as 'without case.' Also, the result implies that HERS-ST implementation may produce benefits, \$2.0 billion (based on 2004 dollars) over BCA period[18], because there are differences in the total benefits between 'with' and

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[18] The BCA period responds to the duration of treatments' lives. For example, a simple resurfacing takes one or two funding periods as a BCA period. However, in case of significant treatments, the BCA period can extend beyond the

‘without’ cases. Eventually, we can observe the efficacy and effectiveness of HERS-ST implementation in terms of monetary values.

Also, from the result, the followings are found:

- Because both ‘with’ and ‘without’ cases show that BCRs are higher than one (except the rural minor arterials without HERS-ST), the treatments recommended by HERS-ST and a worst first strategy are executable. However, the treatments of ‘with case’ are more efficient to produce higher benefits using the same total initial cost as ‘without case.’
- The average BCR for the rural minor arterials without HERS-ST is less than one, 0.156. This is because the worst first strategy recommends treatments for sections where their conditions are under resurfacing and reconstruction criteria even though the treatments are not efficient.Although the total benefits are identified in Table 32, agency, user, and external benefits are not distinguished. Hence, maintenance costs (i.e., agency costs), user costs, and emissions costs (i.e., external costs) in Table 31 are used to estimate how much these costs are reduced if HERS-ST is implemented during the funding periods. Since those are unit costs at the initial, FP 1, and FP 2, they are added to get average unit costs in each funding period. Then, the average unit costs are multiplied by miles or VMT for each funding period. After that, the costs in FP 1 and FP 2 are added to obtain total costs over two funding periods (i.e., 10 years). The differences between the ‘with’ and ‘without’ HERS-ST costs represent the benefits of HERS-ST implementation. The calculations and results are as follows:

Maintenance Costs (Agency Costs)

- With case : (\$215,792+\$128,345)/2 × 1,621.4 × 5/1,000 + (\$128,345+\$105,660)/2 × 1,621.4 × 5/1,000 = 2.3 (million)
- Without case : (\$215,792+\$290,192)/2 × 1,621.4 × 5/1,000 + (\$290,192+\$152,946)/2 × 1,621.4 × 5/1,000 = 3.8 (million)
  Savings in agency costs = 3.8 – 2.3 = 1.5 million

User Costs

- With case : (\$850+\$844)/2 × (2,115mil+2,346mil)/2 × 5/1,000 + (\$844+\$844)/2 × (2,346mil+2,576mil)/2 × 5/1,000 = 19,831.6 (million)
- Without case : (\$850+\$878)/2 × (2,115mil+2,307mil)/2 × 5/1,000 + (\$878+\$862)/2 × (2,307mil+2,568mil)/2 × 5/1,000 = 20,154.6 (million)
  Savings in user costs = 20,154.6 – 19,831.6 = 323.0 million

Emission Costs (External Costs)

- With case : (\$28.744+\$18.531)/2 × (2,115mil +2,346mil)/2 × 5/1,000 + (\$18.531+\$12.144)/2 × (2,346mil+2,576mil)/2 × 5/1,000 = 452.3 (million)
- Without case : (\$28.744+\$18.512)/2 × (2,115mil + 2,307mil)/2 ×5/1,000 + (\$18.512+\$18.502)/2 × (2,307mil+2,568mil)/2 × 5/1,000 = 486.8 (million)
  Savings in external costs = 486.8 – 452.3 = 34.5 million

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end of the overall analysis period (i.e., 20 years in this case study) (U.S. DOT and FHWA, 2005).

Table 32. COSTS AND BENEFITS OF WITH AND WITHOUT CASES

Field			With HERS-ST				Without HERS-ST				(With HERS-ST) – (Without HERS-ST)			
			Total	Breakdown of Total			Total	Breakdown of Total			Total	Breakdown of Total		
				Rural		Urban		Rural		Urban		Rural		Urban
				Principal	Minor	Principal		Principal	Minor	Principal		Principal	Minor	Principal
FP1	Total Initial Cost ($thousand)	1	553,170	396,460	17,464	139,244	234,350	107,201	58	127,090	318,820	289,259	17,406	12,154
	Average BCR	2	8.635	9.905	4.538	5.532	3.901	5.655	0.156	2.424	n.a.	n.a.	n.a.	n.a.
	Total Benefits ($thousand)	1×2	4,776,623	3,926,936	79,252	770,298	914,199	606,222	9	308,066	3,862,424	3,320,715	79,243	462,232
FP2	Total Initial Cost ($thousand)	3	226,091	123,261	84,343	18,486	540,585	349,928	74,004	116,652	-314,494	-226,667	10,339	-98,166
	Average BCR	4	5.963	7.713	3.552	5.295	5.881	7.045	3.822	3.696	n.a.	n.a.	n.a.	n.a.
	Total Benefits ($thousand)	3×4	1,348,181	950,712	299,586	97,883	3,179,180	2,465,243	282,843	431,146	-1,831,000	-1,514,531	16,743	-333,262
Total	Total Initial Cost ($thousand)	5	779,261	519,721	101,808	157,731	774,935	457,129	74,062	243,742	4,326	62,592	27,746	-86,011
	Average BCR	6	7.860	9.386	3.721	5.504	5.282	6.719	3.819	3.033	n.a.	n.a.	n.a.	n.a.
	Total Benefits ($thousand)	5×6	6,124,991	4,878,101	378,828	868,151	4,093,380	3,071,464	282,852	739,212	2,031,612	1,806,637	95,975	128,939

Notes: 1) Monetary values are based on 2004 dollars.

2) *Italics* are derived from HERS-ST analysis outputs.

From the results, HERS-ST implementation results in the total benefits, \$359.0 million, over 10 years. The benefits consist of \$1.5 million in agency benefits, \$323 million in user benefits, and \$34.5 million in external benefits. The values are based on 2004 dollars.

Figure 71 depicts the conceptual benefits of HERS-ST implementation to illustrate the difference between the benefits of \$2.0 billion over the BCA period and the benefits of \$359 million over 10 years. The upper figure shows the benefits produced by treatments in FP 1, while the lower figure shows the benefits produced by treatments in FP 2. Although this case study focuses on FP 1 and FP 2 as an analysis period, the benefits accrue beyond the funding periods. The sum of the benefits from FP 1 to an *n* th funding period in the upper figure and the benefits from FP 2 to an *m* th funding period in the lower figure responds to \$2.0 billion over BCA period. In the meantime, the sum of the benefits in FP 1 in the upper figure and the benefits in FP 2 in the lower figure is worth \$359 million over 10 years. Although we estimated the benefits, it is difficult to determine the duration of the BCA period and the exact benefits over 10 years using the outputs of HERS-ST.

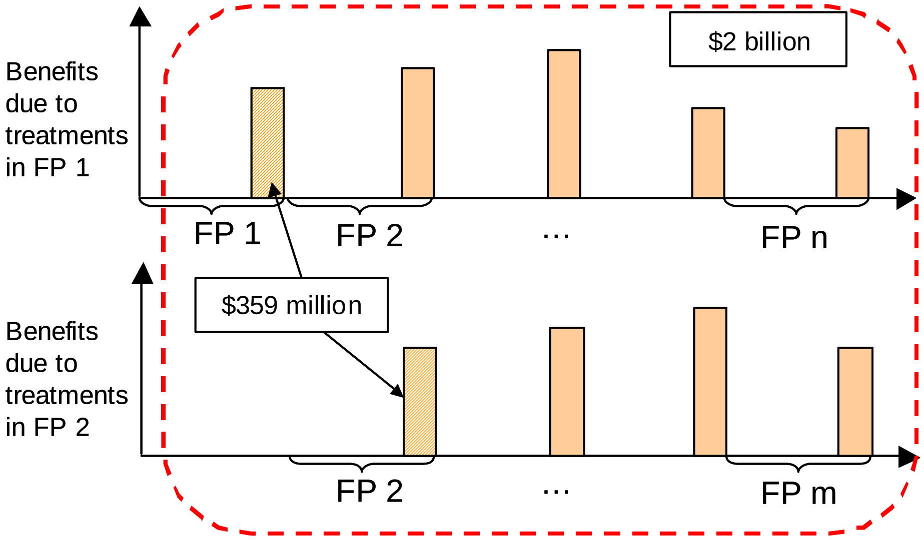

Figure 71. Conceptual benefits of HERS-ST implementation

Investment Justification

Given the quantified total net benefits of HERS-ST implementation, we can compare the benefits to HERS-ST implementation costs to justify investment in HERS-ST implementation. Since there are no available data related to the implementation costs, this discussion of whether the benefits exceed HERS-ST implementation costs remains an exploration from the point of view of net social welfare. Using the quantified total benefits, the following are addressed:

- If an agency spends implementation costs less than \$359 million over 10 years, the agency can justify the investment in HERS-ST implementation, or
- If an agency spends implementation costs less than \$2.0 billion over 25 years, the agency can justify the investment in HERS-ST implementation.

Since the benefits $359 million do not include entire benefits over 10 years, the amount in the first point should be higher than $359 million. In the second point, a BCA period is specified as 25 years. Because a simple resurfacing takes one or two funding periods (U.S. DOT and FHWA, 2005), it is assumed that treatments including reconstruction take four funding periods, that is, 20 years. Then, the first 5-year funding period is added. Despite the incompleteness of the analysis and assumptions, these can be criteria to justify investments in terms of the positive net present value or benefit-cost ratio higher than 1.0, if HERS-ST implementation costs are available. It is not expected that HERS-ST implementation costs would approach $359 million over 10 years because HERS-ST is a free application distributed by FHWA. A similar analysis can be completed from the point of view of the agency. To make this discussion more robust, it is necessary to calculate the exact benefits over a specific analysis period and compare it to the actual implementation costs.

These results are also subject to the limitations of HERS-ST. For example, HERS-ST makes recommendations based on "need" so that the benefits of preventative maintenance are not fully realized.

Lessons Learned

This case study employed the quasi analysis design that simulates actual performance, such as pavement condition, before and after HERS-ST implementation using 'with and without data' because of the lack of actual data related to highway inventories and performance. Like the VTrans' case study, the quasi analysis design contributed to the assessment of benefit quantification in this case study, although actual data are not available. In order to estimate the benefits of HERS-ST implementation, this case study utilized the capability of HERS-ST per se.

The descriptive analysis used with and without data to show the differences between various performance measures provided by HERS-ST between the 'with' and 'without' cases. The differences can be interpreted as: the efficacy showing whether HERS-ST works or not, and the effectiveness by identifying how much HERS-ST improves performance such as pavement condition.

Under the umbrella of the descriptive analysis using with and without data, the regression analysis and BCA were conducted. The model employed AADTs and the use of HERS-ST for independent variables and traffic weighted average pavement conditions for a dependent variable. The model indicated that the use of HERS-ST improves pavement conditions at the network level. However, the small sample size did not yield statistically significant results. The improvement suggested the efficacy and effectiveness of HERS-ST implementation, but further analysis is needed.

Similar to the VTrans case study, the results of the descriptive analysis and regression analysis implied how much the HERS-ST improves resource consumption (i.e., efficiency) since 'with' case uses almost the same amount of budget as 'without' case.

Due to the lack of costs data related to HERS-ST implementation, a comprehensive BCA could not be completed using the net present value and benefit-cost ratio methods. However, the results of HERS-ST identified positive total benefits, including agency, user, and external benefits, between the 'with' and 'without' cases. The benefits can be used for assessment to see whether the investment in HERS-ST implementation is justified and when the investment can be recovered by comparison with the costs for implementation and operation.

Concerning the analysis of benefits estimated by HERS-ST, there are three issues to be addressed to further investigate HERS-ST implementation as follows:

- 'Without case' is not completely based on a worst first strategy because HERS-ST automatically selected treatments for 7 sections in FP 1 and 8 sections in FP 2 among 283 sections. Hence, the reason why the treatments are assigned by HERS-ST must be determined and then all treatments should be assigned by the worst first strategy.
- This case study assumes that a worst first strategy takes resurfacing and reconstruction treatments. Probably, the degree of improvements changes the benefits. For example, a worst first strategy that takes only reconstruction may have different benefits compared to 'with case.' Hence, it is worth conducting a case study using different treatments.
- Since HERS-ST does not provide benefits for each funding period, in terms of agency, user, and externality with respect to highway functional class, this case study could not analyze the results from those perspectives in detail. If HERS-ST provides those benefits in its outputs, the analysis would have a detailed knowledge of the benefits of HERS-ST implementation. Further development of HERS-ST is required.

The outcomes of this case study showed the potential of HERS-ST's functions to quantify the benefits of not only HERS-ST per se but also other AMS and tools as an analysis tool because HERS-ST calculates detailed benefits based on elaborate functions derived from numerous past studies, although there is a constraint that analysis subjects are limited to roads. The constraint can be eliminated if various asset types such as bridges, signs, and safety facilities are added in HERS-ST. This allows us to compare investments in different assets' management and to obtain a more appropriate budgeting plan for asset management with the HERS-ST analysis function. In order to achieve this modification, data for inventory and treatment alternatives for other assets, functions to estimate impacts of the alternatives, and budgets for development are required.

HERS-ST may be used to conduct further studies such as: verifying benefits estimated by past studies; estimating benefits at the national level if all DOTs implement HERS-ST or other AMS and tools; and assessing whether HERS-ST or other AMS implementation is beneficial to an agency that is considering implementation from now. Also, for an agency that has implemented HERS-ST or other AMS and tools, HERS-ST can assess: how many various external influences on management decisions (e.g., political decisions, urban development, economic growth, etc.) exist and produce benefits or negative benefits (i.e., costs) using the comparison based on treatments recommended by HERS-ST or other AMS (i.e., 'with case') using the expected highway performance data and actual treatments; and how many benefits have been produced by HERS-ST or other AMS implementation on highway management using the comparison between based on actual treatments and treatments based on a worst first strategy (i.e., 'without case').

Summary

This case study identified the benefits of HERS-ST derived from two different scenarios simulating performances with HERS-ST and without HERS-ST. The predicted performances are based on analysis functions in HERS-ST per se. Using the three methods, the following observations are made:

- Descriptive analysis using with and without data, a quasi before and after data, showed that the ‘with case’ is superior to the ‘without case’ with respect to performance measures related to agency, user, and external benefits. Also, HERS-ST implementation increases the effectiveness, measured in terms of the area under the performance curve, by 10%.
- Regression analysis showed the benefits of HERS-ST both at the network and section levels. In the network level, HERS-ST improves traffic weighted average pavement condition by 0.388 points.
- HERS-ST estimated the benefits of ‘with’ and ‘without’ cases. The differences, $359 million over 10 years and $2.0 billion over 25 years, are the approximate benefits of HERS-ST implementation consisting of savings of agency, user, and external costs.
- To justify the investment in HERS-ST implementation, the costs for HERS-ST implementation and operation are needed. However, it is not expected that HERS-ST implementation costs would approach $359 million over 10 years.

Given the results above, we recognized that HERS-ST implementation produces benefits. The benefits can be observed as the efficacy and effectiveness of implementing HERS-ST - the differences between ‘with’ and ‘without’ cases, and efficiency – the ratio of benefits to costs for M&R treatments. Also, the investment in HERS-ST implementation can be justified if HERS-ST implementation and operating costs are available.

Chapter 5. GENERIC METHODOLOGY

After developing the framework using the three analysis methods to quantify the benefits of AMS implementation and to justify investment in AMS implementation in Chapter 3, the framework was applied to two case studies using different AMS in Chapter 4. From the results of the case studies, this chapter summarizes a generic methodology. The generic methodology can be applied to any assets, and is presented in terms of what kinds of methods can be used with respect to evaluation design, and how the methods can be used for quantifying the benefits in light of the 3Es. Also, the generic methodology describes how to justify investment in AMS implementation. Furthermore, the chapter addresses the application of the generic methodology and discusses whether the implementation of AMS is beneficial to improving agencies' business performance, users' performance, and environmental impacts from the results of the case studies.

5.1. From Specific Systems in Case Studies to AMS in General

In Chapter 4, the implementations of two different systems, PMS and HERS-ST, were analyzed using the framework. The case studies showed the applicability of the framework to quantify the benefits of PMS/HERS-ST implementation and to justify investment in HERS-ST implementation. Since these AMS focus on pavements and investments in highway systems, it is necessary to discuss whether the framework can be applied to any AMS dealing with other assets such as bridges, tunnels, transit systems, ports, and so on. Since the framework is associated with various data, it is important to focus on data.

The framework includes three analysis methods: descriptive analysis, regression analysis, and BCA. Concerning the descriptive analysis and regression analysis, these methods require several performance measures associated with a focused asset. To conduct an *ex post facto* evaluation using before and after data (i.e., time series data), the data need to include the performance measures used in the descriptive analysis and regression analysis. To conduct an *ex post facto* evaluation and *ex ante* evaluation using with and without data, we need to predict future performances based on past or current performance with respect to the performance measures used in the analyses. To obtain the predicted performance measures, simulations are required. In the HERS-ST case study, pavement conditions and AADT were used as performance measures. Then, predicted pavement conditions and AADT were simulated based on a deterioration model, speed model, and travel forecast model in HERS-ST while taking into account various data related to infrastructure, traffic, and treatments and consequences, as illustrated in Figure 72. Hence, the *ex ante* evaluation needs additional data to simulate predicted performance in addition to performance measures used in the descriptive analysis and regression analysis.

The third analysis method, BCA, estimates agency, user, and external costs. Hence, in both the *ex post facto* evaluation and *ex ante* evaluation, BCA requires data related to cost valuation. For example, the HERS-ST case study analyzed agency, user, and external costs using various data listed in the three valuation components, agency, user, and externality, with respect to infrastructure, traffic, and supplements in Figure 72.

From the observation, the data addressed in Table 33 are required. As we can see, from the *ex post facto* evaluation using before and after data to the *ex ante* evaluation, and from the descriptive analysis and regression analysis to BCA, the number of types of data required increases.

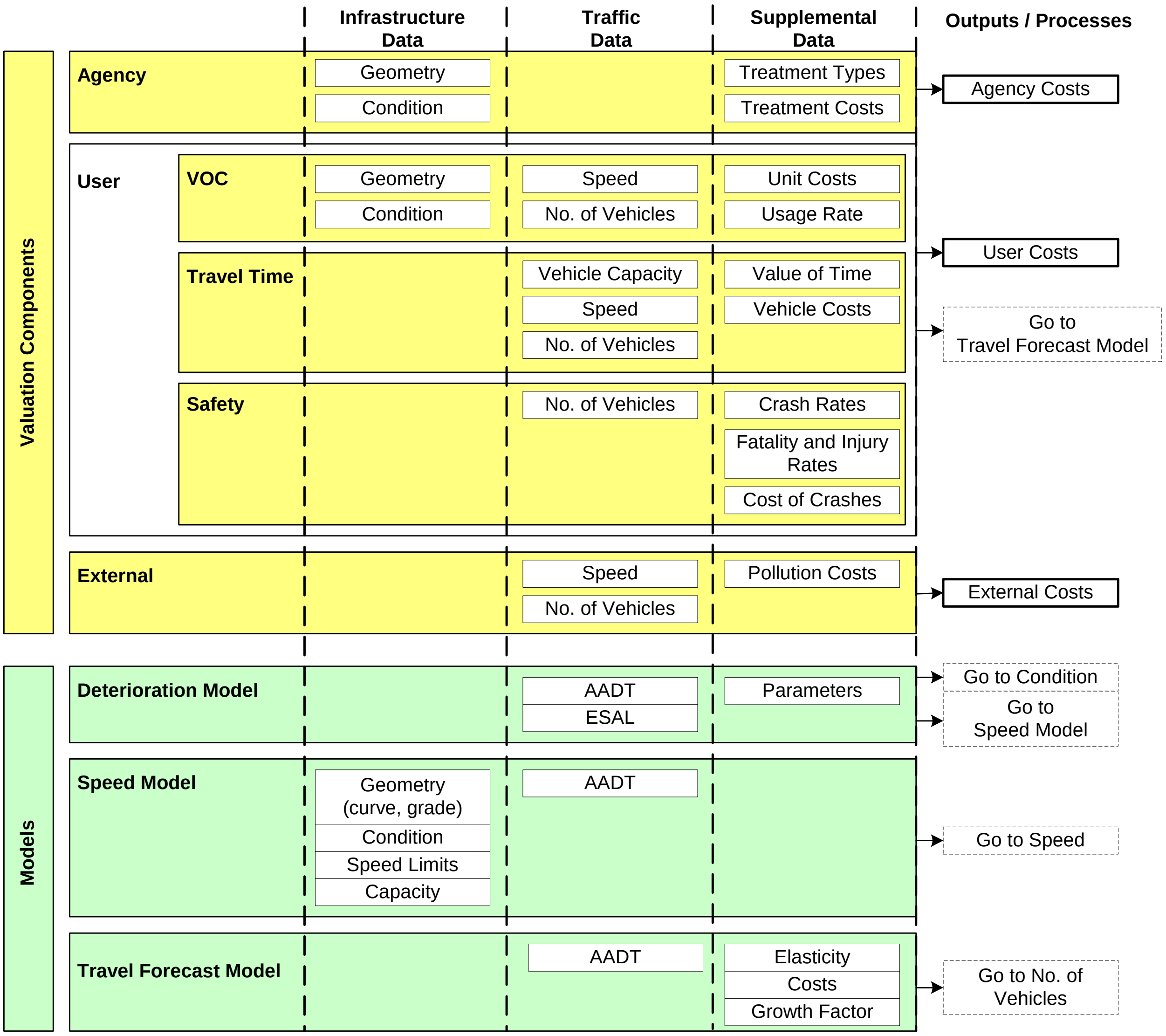

Figure 72. Data used by HERS-ST with respect to valuation components and models

Based on the required data, we recognize that those data may be needed in order to apply the framework to AMS focusing on other assets rather than pavements and highways. It is important to consider what kinds of data are needed if different assets are the subject, because the required data are different from pavement to bridge and because the purpose of infrastructure, user, and associated benefits and costs are different. Probably, collecting cost valuation data may be difficult because user and external costs incurred by other assets have not been explicitly articulated by researchers compared to those incurred by pavements and highways. In that case, although the descriptive analysis and regression analysis can be conducted to quantify the benefits of AMS, investment in AMS cannot be justified due to the lack of cost valuation data needed by BCA. If all required data are prepared, the framework is applicable to any AMS and then both benefit quantification and investment justification can be conducted. Except for the data, the evaluation design and analysis methods can be applied to any asset.

Table 33. REQUIRED DATA

Analysis Methods	*Ex Post Facto*		*Ex Ante*
	Before and After Data	With and Without Data	With and Without Data
Descriptive Analysis	• Time series data with respect to performance measures	• Time series data with respect to performance measures • Predicted performance measures based on simulation • Data for simulation	• Past or current performances • Predicted performance measures based on simulation • Data for simulation
Regression Analysis	• Time series data with respect to performance measures	• Time series data with respect to performance measures for 'with case' • Predicted performance measures based on simulation • Data for simulation	• Past or current performances • Predicted performance measures based on simulation • Data for simulation
Benefit-Cost Analysis	• Time series data with respect to performance measures • Data for cost valuation	• Time series data with respect to performance measures for 'with case' • Predicted performance measures based on simulation • Data for simulation • Data for cost valuation	• Past or current performances • Predicted performance measures based on simulation • Data for simulation • Data for cost valuation

5.2. A Generic Methodology

The type of analysis is determined by: whether AMS is already implemented; and whether time series data are available before and after AMS implementation. The data include performance measures such as pavement conditions, traffic conditions, and emissions. Also, to quantify the benefits of AMS implementation, equivalent data listed in Figure 72 are required as HERS-ST is performed.

Figure 73 depicts the decisions involved in evaluation design. If an agency has implemented AMS and time series data are available, they can use an *ex post facto* evaluation. The *ex post facto* evaluation is one of two types as follows:

- Before and After: a comparison between actual performances before and after AMS implementation, and
- With and Without: a comparison between predicted performance if AMS had not been implemented as quasi performance before AMS implementation and actual performance after AMS implementation. The predicted performance can be simulated based on a strategy before AMS implementation such as a worst first strategy.

If an agency has not implemented AMS or if time series data are not available in an agency that has implemented AMS, an *ex ante* evaluation is used to compare two different simulated future performances based on two strategies: a worst first strategy ('without case') and an AMS optimization strategy ('with case'). This is a quasi comparison of before and after.

The *ex post facto* and *ex ante* evaluations using with and without data need to simulate future performances. Although the use of simulation models is required, developing simulation models is a time consuming and complex task. As this research is performed, we can use AMS per se to simulate future performances instead of developing simulation models. If AMS calculate the benefits of AMS implementation in terms of monetary value as well, we can quantify the monetary benefits and justify investment in AMS implementation. Hence, the use of AMS to simulate future performances is strongly recommended.

The comparisons of the performances between ‘before’ and ‘after’ (or ‘with’ and ‘without’) AMS implementation in the three evaluations show the differences in performances, which represent the benefits of AMS implementation. To quantify the benefits of AMS implementation, the description analysis, regression analysis, and BCA are used.

The discussion in Chapter 3 identified the AMS implementation needed to articulate the efficacy, effectiveness, and efficiency (3Es) of AMS implementation. This need responds to the first objective of the primary research goal: Analyze whether AMS implementation contributes to the improvement of agencies’ performance and reduction of costs for M&R. The methods to articulate the 3Es using the generic methodology are explained as follows:

- Efficacy shows whether AMS work or not (Checkland, 1999). The efficacy can be recognized by the difference in performance between ‘before’ and ‘after’ or between ‘with’ and ‘without’ using the descriptive analysis and regression analysis. Also, the BCA can articulate the efficacy using the net benefits (i.e., benefits including reduction in agency, user, and external costs minus M&R costs), and the ratio of benefits to costs for M&R treatments.
- Effectiveness identifies the degree to which AMS achieve the agency’s asset management goals (Checkland, 1999). Effectiveness is recognized by the difference, but needs to be addressed in term of extent or degree. If the degree is addressed, an agency can observe to what extent asset conditions meet their asset management goals compared to the case of ‘before’ or ‘without.’ The results of descriptive analysis and regression analysis, and BCA can articulate the effectiveness.
- Efficiency identifies optimal use of resources using the ratio of output or outcome to input of AMS (Checkland, 1999). Efficiency can be articulated by the comparison of the ratios of benefits to costs for M&R treatments between ‘before’ and ‘after’ or ‘with’ and ‘without.’ If the costs for M&R before and after (or with and without) AMS implementation are available, the different ratios of performance (e.g., pavement condition) to the costs between before and after (or with and without) can address the efficiency of AMS implementation. The three analysis methods are capable of obtaining the efficiency.

Using the quantified benefits of AMS implementation, AMS implementation should be justified by BCA using the comparison between the benefits of AMS implementation and costs for AMS implementation and operation. This corresponds to the second objective in the primary research goal: Demonstrate that benefits derived from AMS implementation exceed costs for implementation and operation. Since agency, user, and external benefits between ‘before’ and ‘after’ or ‘with’ and ‘without’ can be quantified in the previous step, BCA can compare the benefits to the costs for AMS implementation and operation. We can justify investment in AMS implementation if the difference between the quantified benefits and costs for AMS implementation and operation is positive or if the ratio is over 1.0. This represents the efficiency of AMS implementation with respect to AMS implementation and operation costs.

However, it is difficult to justify investment in AMS implementation in case of using before and after data, because the comparison between ‘before’ and ‘after’ does not utilize mutually exclusive alternatives. Also, AMS implementation costs may be distinguished in 'before' and 'after,' because of incremental AMS development (Mizusawa 2007). Hence, practically, BCA uses approximate benefits and costs to justify investment as Hudson et al. (2001) and Cowe Falls and Tighe (2004) conducted.

Table 34 summarizes the three methods based on the experience gained in this research. As described, all analysis methods are applicable to quantify the benefits of AMS implementation. Since benefits are accrued over years, the benefits identified in the three analysis methods may fluctuate over the length of the analysis periods. Therefore, sensitivity analysis to see the effect of analysis periods is needed. Also, the application of the methods to articulate the 3Es is summarized in Table 35.

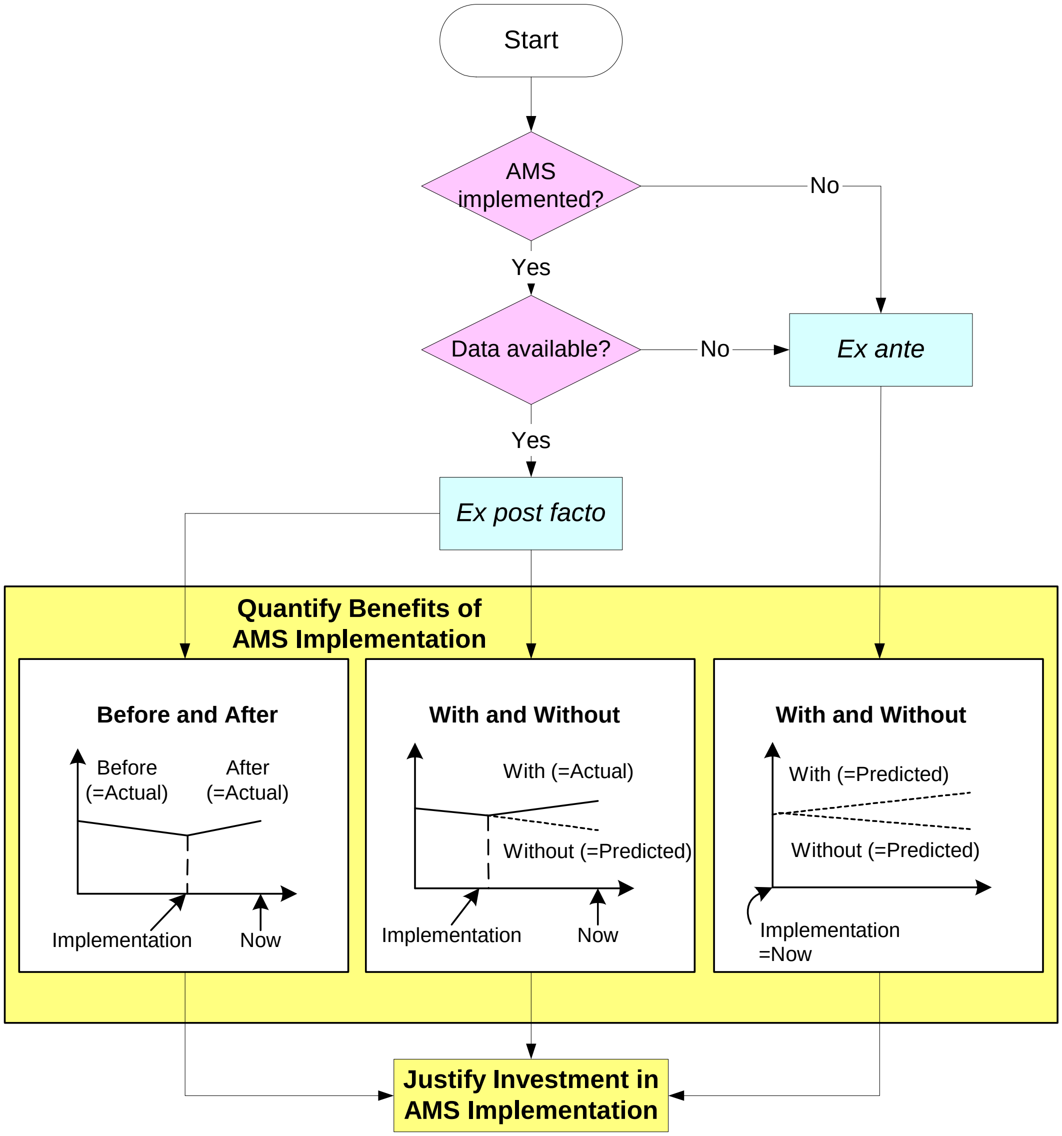

Figure 73. Flow diagram

It is important to bear in mind that predicted data used in the comparison between 'with' and 'without' cases based on an *ex ante* evaluation will not indicate actual future performance due to uncertainties, that is, the impacts of external influences such as political decisions, urban development, economic growth, and so on, and the limitations of simulation. Figure 74 shows the predicted performance with and without AMS based on the *ex ante* evaluation. The solid line and dashed line represent hypothetical data drawn from simulations to depict the predicted performance based on M&R treatments recommended by the AMS (i.e., 'with AMS') and the predicted performance based on a worst first strategy (i.e., 'without AMS'), respectively. The actual pavement conditions may differ from the predicted conditions due to the external influences on asset management decisions. Because of the external influences on asset management, the actual pavement conditions in the future may not exactly trace the predicted lines in Figure 74. The predicted actual pavement conditions, with and without AMS, can be expressed in terms of hypothetical confidence intervals.

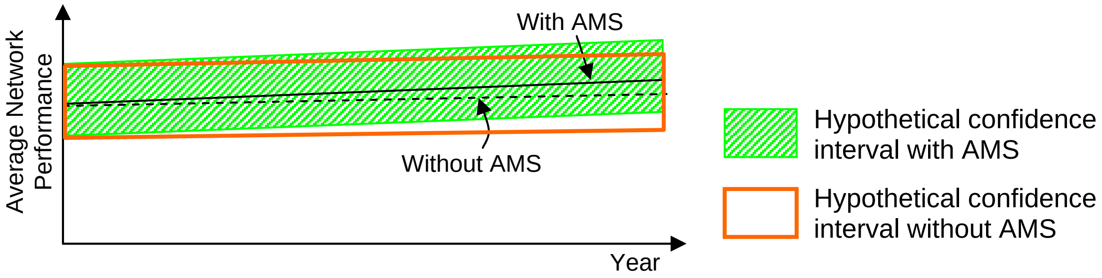

Figure 74. Predicted performances with and without AMS based on ex ante evaluation

How can we observe the impacts? Figure 75 provides a good solution. The difference between the predicted performance with AMS and the predicted performance without AMS represents the effect of AMS implementation (①) observed by the *ex ante* evaluation using with and without data. This effect includes the effect of AMS implementation and the impacts of the external influences because of the predicted performances. Also, the effect of AMS implementation based on the *ex post facto* evaluation responds to the difference between the actual performance with AMS and the predicted performance without AMS (②). This effect based on the *ex post facto* evaluation does not include the impacts of the external influences because the actual performance with AMS is used. As we can see, the difference between ① and ②, that is, ③, represents the impacts of the external influences. This shows the degree of conformity of the agency's business to the M&R program recommended by AMS. Hence, to analyze the impacts of external influences, we can use the comparison between with and without data based on an *ex post facto* evaluation and with and without data based on an *ex ante* evaluation as demonstrated in Figure 75. Needless to say, this comparison is limited to the observation of past impacts.

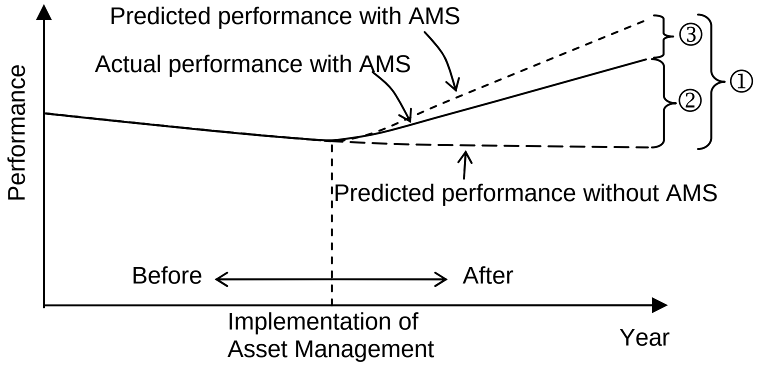

Figure 75. Relationship between effects of AMS implementation and impacts of influences

The HERS-ST case study demonstrated that AMS per se could be a tool to quantify the benefits of AMS implementation and justify investment in AMS implementation, because AMS have functions to simulate performances and benefits and costs produced by M&R treatments so that AMS can provide an M&R program, which is the objective of AMS. In order to simulate asset conditions in the past and future required by *ex post facto* and *ex ante* evaluations, however, AMS should allow users to input specified M&R strategies. There are many AMS existing in a market, and it is expected that their simulation functions are different from each other. When applying AMS for simulation, we have to investigate AMS functions and determine appropriate AMS.

This research focuses on the benefits of AMS implementation at the network level, because AMS supports an entire asset system and because we need to justify investment in AMS implementation for the entire system. This is a rational approach to observe the benefits in the network level. Probably, one may argue that we can analyze asset performances in a section level as well. Figure 76 depicts the conceptual performance at a section level based on an *ex ante* evaluation. The upper figure shows the predicted performances with AMS and without AMS in one section level. Although we assume that improved performance based on an AMS recommendation is better than that based on a worst first strategy, the situation cannot be observed all the time because the timing of treatments and deterioration conflict with the expectation as the upper figure illustrates. Hence, when assessing the predicted performance with and without AMS at the section level, we cannot determine the benefits of AMS implementation by the performance. In an *ex post facto* evaluation, section level analysis is not appropriate as well.

The lower figure shows the predicted performances with and without AMS in an aggregate section level. Again, we can assume that improved performance based on AMS recommendations is better than that based on a worst first strategy. Using average section performance, we can compare the predicted performances with and without AMS in an aggregate section level. However, the regression analysis has a problem of autocorrelation between members of a series of observations ordered in time or space when using panel data (Gujarati, 2003). Although there is an example of the regression analysis using panel data (Hudson et al., 2001), it is not recommended to use the regression analysis in an aggregate section level because its result would be distorted by the temporal and spatial correlation. This issue is discussed further in Mizusawa (2007). An *ex post facto* evaluation may encounter the same problem in the regression analysis.

Overall, it is better to focus on the benefits of AMS implementation at the network level, although we can analyze asset performances in the section level, because one section level does not show the benefits of AMS implementation in the entire network, and because the aggregate section level has to deal with the problem of autocorrelation in the use of the regression analysis.

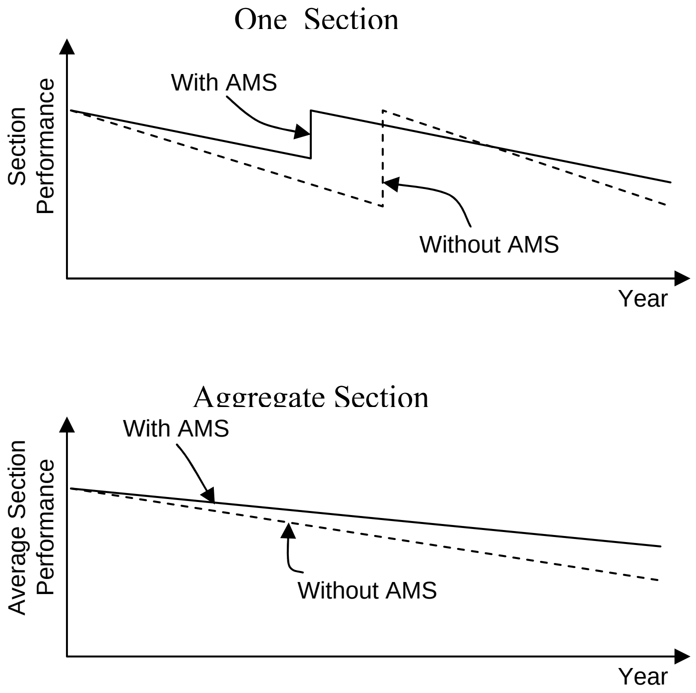

Figure 76. Conceptual performance at a section level

Table 34. SUMMARY OF GENERIC METHODOLOGY

Evaluation Design			Ex Post Facto		Ex Ante	Notes
Data Type			Before and After	With and Without	With and Without	
Comparison			• Performance before and after AMS implementation using actual data	• Performance with (i.e., after: actual data) and without (i.e., before: predicted data) AMS implementation	• Performance with (i.e., after: predicted data) and without (i.e., before: predicted data) AMS implementation	
Requirement		Data	• Time series data • Data for cost valuation	• Time series data • Predicted performance measures based on simulation • Data for simulation • Data for cost valuation	• Past or current performance • Predicted performance measures based on simulation • Data for simulation • Data for cost valuation	E.g., highway case (Figure 72)
		Simulation	Not needed	Needed for 'without	Needed for 'with' and 'without'	• AMS can be used for simulation.
Analysis Methods	Quantify Benefits of AMS implementation	Descriptive	Applicable	Applicable	Applicable	• Can perform at network and section levels.
		Regression	Applicable	Applicable	Applicable	• Need sufficient observations. • An aggregate section level encounter with autocorrelation.
		Benefit-cost	Applicable	Applicable	Applicable	• Need unit costs for benefit estimation (user and external benefits). • AMS can be used to estimate benefits and M&R costs.
	Justify investment in AMS implementation	Benefit-cost	Applicable but approximation	Applicable	Applicable	• Need AMS implementation and development costs. • AMS can be used to estimate benefits.
Others			• Difficult to set analysis periods of 'before' and 'after.'	• Predicted data includes uncertainty (i.e., external influences) in performance. • The combination of the comparisons between with and without data based on both *ex post facto* and *ex ante* shows the impact of external influences – the degree of conformity of agency's business to M&R program recommended by AMS.		• Need to perform *ex post facto* and *ex ante* evaluations.
			• The results of the analysis methods will be influenced by the length of analysis period because the benefits of AMS implementation will be accrued.			• Need sensitivity analysis to observe the effect of analysis period.

Table 34. (Continued) SUMMARY OF GENERIC METHODOLOGY

Objective	3Es	Methods	
		Description	Examples
Quantify benefits of AMS implementation	Efficacy Effectiveness	Descriptive analysis with before and after (with and without) data Difference in performance (e.g., pavement condition) between ‘before’ and ‘after’ or between ‘with’ and ‘without’	7) $(TWAPCI_{with}) - (TWAPCI_{without})$ 8) TWAPCI: Traffic Weighted Average PCI
		Regression analysis A coefficient, showing difference in performance, of a dummy variable switching a regression model either to ‘before (without)’ or to ‘after (with)’	9) $TWAPCI = \beta_0 + \beta_1 X + \delta HERS + \varepsilon$
		Benefit-cost analysis Difference in net benefits or the ratio of benefits to initial costs for M&R treatments between ‘before’ and ‘after’ and between ‘with’ and ‘without’	10) $(\text{Net Benefits}_{with}) - (\text{Net Benefits}_{without})$
	Efficiency	Descriptive analysis with before and after (with and without) data Ratios of performance measures to initial costs between ‘before’ and ‘after’ or between ‘with’ and ‘without’ (e.g., increase of performance measures divided by initial costs)	11) $\Delta TWAPCI/(\text{Initial Costs})_{with}$ 12) vs. $\Delta TWAPCI/(\text{Initial Costs})_{without}$
		Regression analysis A coefficient, showing difference in efficiency, of a dummy variable switching a regression model either from ‘before (without)’ or ‘after (with)’	13) $\frac{\Delta TWAPCI}{Initial\_Costs} = \beta_0 + \delta HERS + \varepsilon$
		Benefit-cost analysis Ratios of benefits of AMS implementation to initial costs between ‘before’ and ‘after’ or between ‘with’ and ‘without’	14) $\text{Benefits}/(\text{Initial Costs})_{with}$ 15) vs. $\text{Benefits}/(\text{Initial Costs})_{without}$
Justify investment in AMS implementation	Efficiency	Benefit-cost analysis Total net benefits between net benefits of AMS implementation and total costs for AMS implementation and operation Ratios of total net benefits of AMS implementation to total costs for AMS implementation and operation	16) $\{(\text{Net Benefits}_{with}) - (\text{Net Benefits}_{without})\}$ a. (AMS impl. & ope. Costs) 17) $\{(\text{Net Benefits}_{with}) - (\text{Net Benefits}_{without})\}/$ 18) (AMS impl. & ope. Costs)

Table 35. RESULTS OF CASE STUDIES USING GENERIC METHODOLOGY

Objective	3Es	Methods	VTrans Case Study	HERS-ST Case Study
Quantify benefits of AMS implementation	Efficacy Effectiveness	Descriptive analysis with before and after (with and without) data	From Table 11, $(\text{TWAPC}_{\text{with}}) - (\text{TWAPC}_{\text{without}})$ = 66.0 – 55.9 = 10.1 (all pavement classes) → Efficacy of PMS implementation If an agency sets a goal of CMP at 65.0 points, with case will achieve 1.0 points, while without case will not achieve 9.1 points. → Effectiveness of PMS implementation	From Table 28, $(\text{TWAPSR}_{\text{with}}) - (\text{TWAPSR}_{\text{without}})$ = 3.67–3.37 = 0.30 (all functional classes) → Efficacy of HERS-ST implementation If an agency sets a goal of PSR at 3.5 points, with case will achieve 0.17 points, while without case will not achieve 0.13 points. → Effectiveness of HERS-ST implementation
		Regression analysis	Model (8.8) $\hat{TWAPC}_t = 715.8 - 0.0454 AADT_t + (7.7E-07) AADT_t^2 + 10.1 PMS_t$ →10.1: Efficacy of PMS implementation If AADT is available, TWAPC can be obtained and be compared to the goal of CMP. The result will identify the effectiveness of PMS implementation.	See (Mizusawa 2007) $\hat{TWAPSR}_n = 3.728 - (1.613E-07) AADT_n + 0.300 HERS_n$ →Model is not plausible.
		Benefit-cost analysis	Due to lack of data, BCA was not performed.	From Table 32, $(\text{Net Benefits}_{\text{with}}) - (\text{Net Benefits}_{\text{without}})$ = (6,124,991-779,261) – (4,093,380-774,935) = $2,027,286 (thousand) → Efficacy of HERS-ST implementation If an agency sets a goal of net benefits, the effectiveness of HERS-ST implementation can be identified by the comparison between the goal and the net benefits with HERS-ST.

Table 35. (Continued) RESULTS OF CASE STUDIES WITH APPLYING GENERIC METHODOLOGY

Objective	3Es	Methods	VTrans Case Study	HERS-ST Case Study
Quantify benefits of AMS implementation	Efficiency	Descriptive analysis with before and after (with and without) data	From Figure 22, • ΔPCI/(budget)$_{with}$ = (66-65)/\$55million • ΔPCI/(budget)$_{without}$ = (56-70)/\$55 million → with case > without case Efficiency of PMS implementation	From Table 30 and Table 31, • ΔTWAPSR/(Initial Costs)$_{with}$ = (3.583-3.576)/ \$779261(thousand) = 8.98E-09 • ΔTWAPSR/(Initial Costs)$_{without}$ = (3.326-3.576)/ \$774935(thousand) = -3.23E-07 → with case > without case Efficiency of HERS-ST implementation
		Regression analysis	Due to lack of cost data, regression analysis was not performed.	Due to insufficient observations, the following regression model in the network level cannot be performed. $\frac{\Delta TWAPCI}{Initial\_Costs} = \beta_0 + \delta HERS + \varepsilon$
		Benefit-cost analysis	Due to lack of data, BCA was not performed.	From Table 32, 19) Benefits/(Initial Costs)$_{with}$ = 7.860 20) Benefits/(Initial Costs)$_{without}$ = 5.282 → with case > without case Efficiency of HERS-ST implementation
Justify investment in AMS implementation	Efficiency	Benefit-cost analysis	Due to lack of data, BCA was not performed.	From Table 32, {(Net Benefits$_{with}$)–(Net Benefits$_{without}$)}–(AMS Costs) = \$2,027,286 (thousand) – (AMS Costs) → If the difference is larger than 0, then HERS-ST implementation is efficient, that is, investment is justified.

5.3. Application of the Generic Methodology

The two case studies in Chapter 4 employed the comparison between with and without data based on an *ex ante* evaluation to analyze the benefits of PMS and HERS-ST. Although VTrans implemented PMS, it is difficult to determine when PMS was implemented, because VTrans incrementally prepared and implemented PMS over the last two decades. Also, VTrans does not have the complete cost data related to PMS implementation due to the difficulty of extracting PMS implementation costs combined with various expenditures. The HERS-ST case study used available HPMS data consisting of highway inventory and performance data from the State of New Mexico in year 2001 only. For those reasons, the two cases simulated two sets of predicted pavement conditions based on PMS or HERS-ST strategy (i.e., 'with case') and a worst first strategy (i.e., 'without case').

To simulate performances of 'with' and 'without' cases, VTrans case study used PMS and a spreadsheet, respectively. Creating the 'without case' based on a worst first strategy was a time consuming and complex task since required information had to be imported from PMS and since all sections had to be simulated. On the other hand, HERS-ST case study easily completed its analysis because HERS-ST could simulate both cases using its analysis functions.

In the case studies, the with and without data based on an *ex ante* evaluation are used in three analyses: descriptive analysis, regression analysis, and BCA. The descriptive analysis in both case studies showed whether (i.e., efficacy) and how much (i.e., effectiveness) the PMS/HERS-ST improves performance such as pavement condition, traffic condition, and emissions. (The case of VTrans showed improvements in terms of pavement condition only.) The regression analysis showed the efficacy and effectiveness using a dummy variable to represent the use of a PMS/HERS-ST and served as a tool to show the result of descriptive analysis graphically. Also, the results of descriptive analysis and regression analysis in the case studies implied how much the PMS/HERS-ST improves resource consumption (i.e., efficiency) because pavement conditions were improved using the same level of initial costs as the 'without case.' BCA was not successful because there were no available data related to benefits and costs in VTrans case study and because there were no costs data in the HERS-ST case study. However, HERS-ST case study identified the difference in the ratios of benefits to cost for M&R between 'with' and 'without' cases that showed the efficacy and efficiency of HERS-ST implementation. Also, the HERS-ST case study showed the total and partial benefits including agency, user, and external benefits, and might compare the benefits to HERS-ST implementation costs to assess whether the investment in HERS-ST implementation is justified if the costs for implementation and operation are available.

Since time series performance data were not available, an *ex post facto* evaluation using before and after data and with and without data were not conducted in this research. If before and after data included in time series data are available, performance before and after AMS implementation can be analyzed using the three methods. However, there is a problem existing in the comparison between before and after data. That is a difficulty to determine when AMS was implemented because agencies tend to implement AMS incrementally. Depending on the length of the analysis periods, the analysis results will be different. Hence, setting analysis periods of before and after AMS implementation is problematic.

What about the comparison between with and without based on *ex post facto* evaluation? To answer this question, it is necessary to define a M&R strategy (e.g., a worst first strategy), develop a simulation method, and simulate performance without AMS based on the previous M&R strategy using simulation methods. Because the simulation of 'without case,' a quasi of 'before,' is a complex task as illustrated by the VTrans case study, AMS per se with a function to simulate the previously used M&R strategy can be used as a tool to simulate 'without case.' Once 'without case' is simulated, the descriptive analysis and regression analysis can be conducted. For BCA, AMS also can be used as a function to convert the user and external benefits into monetary values.

5.4. Discussion of AMS Implementation

The case studies in Chapter 4 examined the benefits of PMS and HERS-ST. The result of VTrans case study showed that PMS implementation improves pavement condition at 10.1 points on a 0-100 point scale. HERS-ST case study also identified the benefits of HERS-ST in pavement condition at 0.388 points (on a scale of 0 to 5) at the network level. Moreover, the benefits of HERS-ST implementation consisting of agency, user, and external benefits may reach to $359 million over 10 years and $2.0 billion over 25 years. Given those results, we can answer to the following research questions:

- Does an agency increase productivity and decrease costs with AMS?
- Does the public realize user and external cost reductions due to AMS implementation?
- Do the benefits of implementing AMS exceed implementation and operating costs?

The answer to the first question is 'yes.' As described, it is expected that pavement conditions will be improved by the use of PMS/HERS-ST at the network level using the same level of M&R initial costs as 'without case.' Also, the result can be described in which an agency can achieve their desired asset conditions using lower initial costs if PMS/HERS-ST is used. Hence, an agency will increase their productivity per capital investment and decrease costs for M&R per improvements with PMS/HERS-ST.

HERS-ST case study identified $359 million of the benefits of HERS-ST implementation over 10 years. The benefits consist of $1.5 million agency benefits, $323 million user benefits, and $34.5 million external benefits. Given this result, the answer to the second question is 'yes.'

Since the costs for PMS and HERS-ST implementation and operation are not available, it is impossible to answer the third question directly. For VTrans case study, since the benefits are identified by the improvement of pavement conditions, monetary values for the improvements are needed to compare with the costs for PMS implementation and operation. Given the result of HERS-ST case study, the benefits of HERS-ST implementation, $359 million, may exceed implementation and operating costs over 10 years, because FHWA distributes HERS-ST to agencies without charge. Although the HERS-ST operation costs are needed to justify investment in HERS-ST implementation, it is not expected that they would approach $359 million.

Based on the answers to the research questions, the implementation of HERS-ST is beneficial to improving agencies' business performance, users' performance, and environmental impacts. Although this conclusion requires assumptions and predictions, and is based on the case studies, the approach is rational and grounded in widely accepted practices. Because VTrans case study assumed that there is no change in user and external costs, the study could not investigate those costs responding to the second research question. Like the VTrans case study, an assumption may be needed to conduct the process to quantify the benefits of AMS implementation due to a lack of appropriate data and methods, and thus we may not be able to capture the full extent of benefits of AMS implementation. Although the two case studies based on an *ex ante* evaluation simulated future performances such as pavement conditions, the predicted performances cannot completely represent future performances due to external influences such as political decisions, urban development, and economic growth, and the limitation of simulation. Also, two case studies are not enough to represent a big picture of AMS implementation. Therefore, it is important to remember that the results of this research may not completely reflect the reality in the future, and the comparison between the predicted performance and the actual performance should be examined to observe the external influences and the accuracy of simulation if a gap is observed in the comparison.

Furthermore, to conclude that AMS implementation is beneficial, two tasks are required: quantifying the benefits of AMS implementation, and justifying investment in AMS implementation. Even though benefits are observed in terms of the 3Es, a stronger case for AMS implementation is made when the benefits demonstrably exceed the cost for AMS implementation and operation.

PART III: CONCLUSION

AMS are important asset management tools to manage the existing transport system stock, which as aging infrastructure is particularly vulnerable to increasing heavy truck traffic and rapid traffic growth. It is expected that AMS improve asset performance, increase the efficiency of operation and management of assets, and optimize limited budges through efficient asset management.

Although AMS have been developed since the 1970s, there are still several barriers to implementing AMS in transportation agencies. The goals of this research are: to develop a generic methodology for quantifying the benefits of AMS implementation, and to understand AMS implementation for addressing strategic directions for successful AMS implementation.

First, this research focused on the AMS implementation process and barriers and needs in the process of understanding AMS implementation process itself by reviewing studies of implementation of various asset management tools from domestic and international experiences, in terms of policy, technology, institutions, and funding. Then, the experiences were compared to each other to capture what kinds of needs are required for successful implementation in the U.S. with respect to the needs extracted from the international experiences. The comparison showed that the U.S. possesses an environment able to satisfy the needs.

The literature review identified three needs: to explore the role of regulation, to provide AMS guidelines, and to articulate the 3Es. Since the last need, to articulate the 3Es, is critical for successful AMS implementation, and since there are no unified and systematic methods to quantify the benefits of AMS implementation in terms of the 3Es, a framework was developed based on the literature review. This corresponds to one goal of this research.

The framework involves three analysis methods: descriptive analysis using before and after (with and without) data, regression analysis, and BCA. Depending on the implementation of AMS and the availability of time series data related to asset inventory, asset performances, and M&R treatments, the evaluation design is different as follows:

- For an agency that implemented AMS and has available time series data, use before and after data based on an ex post facto evaluation using a comparison between actual performances before and after AMS implementation or use with and without data based on an ex post facto evaluation using a comparison between predicted performance if AMS had not been implemented as quasi performance before AMS implementation and actual performance after AMS implementation.
- For an agency that implemented AMS but has no available time series data and an agency that has not implemented AMS and has no available time series data, use with and without data based on an ex ante evaluation using a comparison between predicted performances with and without AMS implementation.

In order to analyze the framework, this research conducted two case studies. However, due to data availability issues, the case studies applied the ex ante evaluation only. The results showed applicability of the framework to quantify the benefits of AMS implementation in light of the 3Es. Although the justification of investment in AMS implementation was not conducted by BCA in the framework due to the lack of available AMS implementation and operating costs, BCA showed its capability of justifying the investment. Also, the results identified the increases in performances such as pavement conditions and the benefits of AMS implementation consisting of agency, user, and external benefits. The case studies required assumptions and predictions to conclude that AMS implementation contributes to the improvement in agencies' performance and costs for M&R; the benefits derived from AMS implementation exceed costs for AMS implementation and operation. However, the approach was rational and grounded in widely accepted practices.

The contributions of this research are in the following areas:

- Recognized and raised the importance of quantifying the benefits of AMS implementation and of justifying investment in AMS implementation and operation.
- Documented numerous domestic and international AMS implementation experiences.
- Identified the needs for successful AMS implementation The analysis of the domestic and international experiences based on literature review identified various needs categorized into four areas: policy, technology, institutions, and funding.
- Documented the methods to quantify and analyze the benefits of various applications including PMS, transit systems, and ITS. The summaries include research strategy, data used, model, result, pros and cons, and bibliography.
- Recognized the importance of distinguishing among the 3Es – efficacy, effectiveness, and efficiency. Having the definitions, we can promote a better understanding of quantifying the benefits of AMS implementation.
- Developed a framework for a generic methodology using three analysis methods to quantify the benefits of AMS implementation and justify investment in AMS implementation and operation. The development of the generic methodology is a starting point to achieve the goal – quantify the benefits of AMS implementation. This research intended to encourage people who are in charge of asset management, including the author, to reinforce asset management throughout discussion about the methodology.
- Performed two case studies to demonstrate the applicability of the framework. Based on the case studies, agencies can follow the process and may be able to quantify the benefits of their AMS implementation.
- Showed possible benefits of implementations of PMS and HERS-ST in the case studies. The results imply that VTrans and New Mexico would have the same benefits as the results of case studies compared to a worst first strategy if they use PMS and HERS-ST in the future.
- Suggested the use of AMS per se to quantify the benefits of AMS implementation. The case studies showed a possibility of the use of AMS and a need to develop AMS functions in order to quantify the benefits of AMS implementation and justify investment in AMS implementation.
- Articulated a strategy for using the generic methodology with respect to research environment (i.e., the status of AMS implementation and data availability), research objectives (i.e., benefit quantification and investment justification), and the 3Es. Agencies can incorporate the strategy to assess their AMS implementation and then they may achieve successful AMS implementation, that is, continual use of AMS, because they can obtain support from other stakeholders through the dissemination of the assessment result.

This research recommends that transportation agencies conduct the following:

- Needs Assessment: If an agency considers implementing and developing AMS, they can assess the agency's environment with respect to the identified needs for AMS implementation. If they recognize insufficient conditions in a specific need, that point would become a possible barrier to implementing AMS. Once they find the barrier, they can eliminate it and achieve successful AMS implementation.
- Application of Needs: Once they define their barriers and needs, agencies should develop an action plan that addresses how to apply needed resources in detail. For this process, agencies can learn 'how to' from previous best practices and ask national organizations, consultants, and academic to provide technology and knowledge.
- Data Collection: To quantify the benefits of AMS implementation, data is very critical. Asset inventory and performances (e.g., asset conditions, traffic, etc.) and historical M&R treatments data are required. When focusing on different assets other than pavement and highway, it is necessary to take into account what kinds of data are required since different assets use different performance measures and valuation methods
- Benefits Quantification and Investment Justification: Quantifying the benefits of AMS implementation and justifying investment in AMS implementation and operation is a very important monitoring process in asset management to articulate the 3Es of AMS to other stakeholders, politicians and the pubic. Positive results of the 3Es can generate support from the stakeholders. Meanwhile, negative results of the 3Es can reveal the agencies' insufficient points in asset management and give an opportunity to improve the agencies' asset management, thus eventually obtain support from the stakeholders. Since this monitoring process realizes continual AMS implementation and development, the use of the generic methodology suggested in this research is recommended.
- Disseminate Results: Dissemination of the results of the benefits to the stakeholders is strongly encouraged in order to obtain support from them. Importantly, comprehensive dialogues have to be used for dissemination to the stakeholders who are not familiar with asset management.
- Continual Process: Since asset conditions are changing day by day, the five recommendations above have to be continually executed. This continual process strengthens the AMS use and further development in the future.

Again, this research recommends enhancing AMS to quantify the benefits of AMS implementation. As shown in the HERS-ST case study, AMS can be a tool to quantify the benefits because AMS can predict future asset performances and quantify agency, user, and external benefits. Using the performances and benefits, we can articulate the benefits of AMS implementation in terms of the 3Es and justify investment in AMS implementation and operation compared to the costs for AMS implementation and operation. The objective of AMS is to support the systematic process of maintaining, upgrading, and operating physical assets cost-effectively (U.S. DOT and FHWA, 1996). Now, we can add a function for monitoring the condition of physical assets to determine whether they are maintained efficiently and consistently according to the AMS's objective. AMS can have a function to monitor the 3Es of AMS implementation using the capability of quantifying the benefits of AMS implementation besides the functions related to the systematic process. Users need to be able to input historical and/or planned M&R treatments, simulate past and future asset performances, and quantify the benefits obtained from the treatments. The quantified benefits can be used to justify investment in AMS implementation and operation as well as to analyze degree of conformity of the agency's business to M&R program recommended by AMS.

Additional research is required as follows:

- Implementation in transportation agencies. To improve the results, actual inputs from various stakeholders are required.
- Ex Post Facto Evaluation: This research employed an ex ante evaluation due to the difficulties in determining when AMS was implemented, in extracting AMS implementation costs combined with various expenditure, and in obtaining time series data. It is imperative to deal with the difficulties and conduct the ex post facto evaluation to quantify the benefits of AMS implementation.
- Further Case Studies: This research identified further necessary case studies such as: verifying benefits estimated by past studies, estimating benefits at the national level if all agencies implement AMS, and assessing whether AMS implementation is beneficial to an agency that is considering implementation from now. Also, concerning agencies that implemented AMS, external influences can be analyzed by comparing actual asset performance to predicted asset performance.
- AMS: There are many different existing AMS. If different AMS are used for quantifying the benefits of AMS implementation, their different analysis models and valuation methods for agency, user, and external costs may result in different quantity of benefits. Hence, it is imperative to investigate inside AMS and choose the most reasonable AMS among alternatives. In addition, verification of the generic methodology for applying to any other asset types (e.g., bridge, tunnel, and transit) is required.

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APPENDIX A. BENEFITS OF ASSET MANAGEMENT: BACKGROUND

The literature review and background material presented in this appendix describes the benefits and costs of AMS implementation and methods to quantify the benefits of AMS implementation addressed in Chapter 3. The benefits and costs of AMS implementation are explained in terms of theoretical, qualitative and quantitative aspects. The methods to quantify the benefits are summarized from research papers and are utilized to build a generic methodology for quantifying the benefits of AMS implementation in order to break through the most critical barrier – costs.

Benefits and Costs of AMS

This section summarizes the benefits and costs of AMS implementation to understand the background and its application for quantifying benefits derived from AMS implementation. Given the background, we can develop methods to quantify the benefits of AMS implementation. This section begins by reviewing the foundations of Benefit-Cost Analysis (BCA), along with discussion of benefits and costs in this research. Then, the section addresses what kinds of benefits and costs exist in AMS implementation.

Foundation of Benefit and Cost Estimation

The foundation of BCA, including principle and elements, is addressed in the following parts. The principle helps to understand the mechanism of benefits and costs in our society. The elements use an example of transportation system to illustrate how benefits and costs can be captured.

Principles of Benefit and Cost Estimation

To understand how benefits and costs are captured in terms of economics and how those are related to BCA, the following general concepts are important.

Pareto Efficiency

Economics assumes that people try to maximize their well-being (i.e., utility) by using their incomes to purchase the combinations of goods that give them the greatest utility. A set of prices arises that distributes factor inputs (e.g., labor, land, capital, and materials) to firms and goods to individuals in such a way that it would not be possible for anyone to find a reallocation that would make at least one person better off without making at least one person worse off (Weimer and Vining, 2004).

Figure 77 depicts this situation. There are two people who get an allocation of $1,000. Potentially, either person 1 or person 2 can get $1,000. The line segment connecting ($1,000, $0) and ($0, $1,000) is called as the Potential Pareto Frontier. Currently, person 1 receives $100 while person 2 receives $200. This point ($100, $200) is the status quo. Since no one is worse off if the allocation is changed to person 1 gets allocation up to $800 and person 2 gets $200. Also, person 2 can get an allocation up to $900 when person 1 gets $100. The line segment connecting the two points ($800, $200) and ($100, $900) represents the Pareto Frontier. As can see, the shaded area surrounded by ($800, $200), ($100, $900), and ($100, $200) depicts all possible improvements compared to the status quo, that is, Pareto improvements. A Pareto improvement is fundamental to BCA because it helps to define an efficient project. The concept of Pareto

Efficiency is that society is better off when a change (e.g., a political intervention, a transportation project, etc.) makes at least one individual better off, and no one is made worse off.

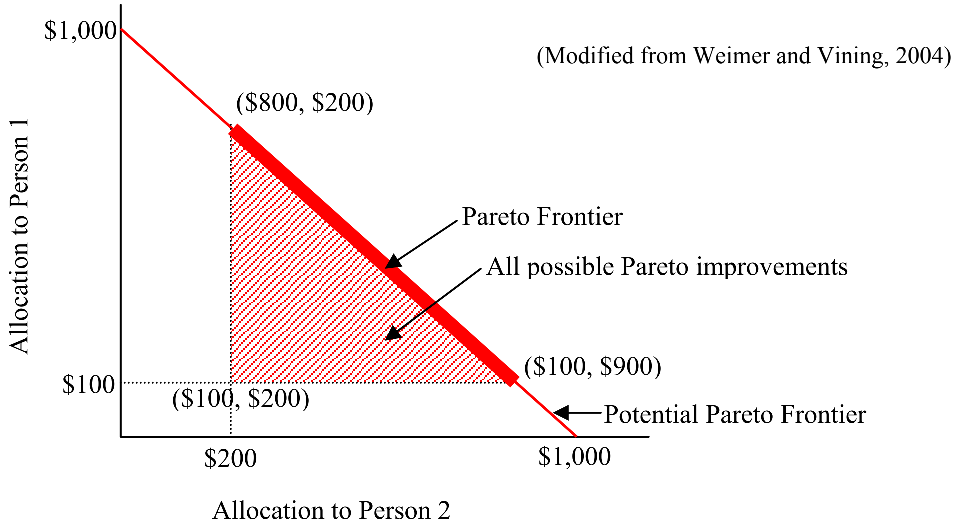

Figure 77. Pareto and potential Pareto efficiency

Kaldor-Hicks Criterion

Although Pareto Efficiency assumes that society is better off when a change makes one individual better off and no one is made worse off, in practice it is almost impossible to make any change without making at least one person worse off. For example, if a highway project produces benefits such as savings in user travel time and economic growth that exceed costs for construction and environment, the project will be executed. This is the principle of BCA. However, the project makes someone worse off because he/she may suffer from relocation from where he/she used to live and environmental pollution such as emission and noise released from vehicles running on the highway. In order to alleviate those problems, he/she will be compensated with money and/or environmental safeguards by those who get the benefits.

The transfer of benefits from one group or individual is known as Kaldor-Hicks improvements. This situation explained by the Kaldor-Hicks improvements is depicted in

Figure 78. As explained in the previous section, the shaded triangle area surrounded by ($800, $200), ($100, $900), and ($100, $200) depicts all possible Pareto improvements in which society is better off when a change makes one individual better off and no one is made worse off. In addition, there are two parallelogram-shaded areas adjacent to the horizontal and vertical axes that represent all possible Kaldor-Hicks improvements. Within these areas, person 1 or person 2 is worse off due to a change compared to the status quo ($100, $200).

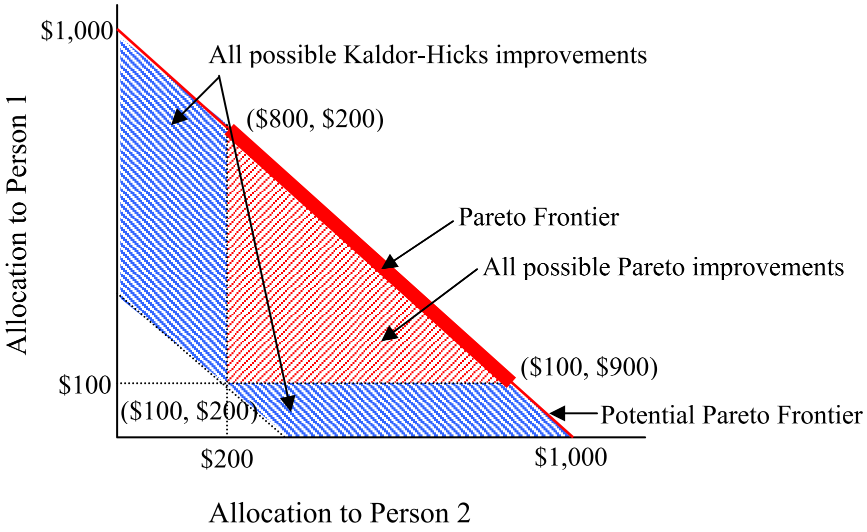

Figure 78. Kaldor-Hicks and Pareto

If those who are made better off could, in theory, compensate those who are made worse off and lead to a Pareto improvement outcome, an outcome of the Kaldor-Hicks improvements is more efficient than that of the Pareto improvements because the number of allocation patterns for person 1 and person 2 of the Kaldor-Hicks improvements is larger than those of the Pareto improvements. As a result, a more efficient outcome would make some person worse off, and then he/she will be compensated by those who benefit.

The basic principle underlying BCA is the Kaldor-Hicks criterion: "*a change should be adopted only if those who will gain could fully compensate losers and still be better off.*" It is argued that the criterion is justifiable for society as a whole to make some worse off if a change brings a greater gain for others. This is called as "*utilitarianism ("the surplus of pleasure over pain – aggregated across all of the inhabitants of society") that the pure Pareto criterion avoids*" (Weimer and Vining, 2004; Wikipedia, 2006).

Demand, User Cost, and Supply Functions

This part explains a demand function, a user cost function, and a supply function, which are fundamental elements of BCA to estimate benefits. The nature of the functions is illustrated in order to explain how to estimate the benefits described in the following parts. A transportation system that is sensitive to traffic volume is used to illustrate the concepts in this part.

Demand Function

A demand function depicts the dependent relationship between the traffic volume 'demanding' use of a facility and the various factors which influence the traffic volume demanded, including user cost that represents price of travel. Travel demand is a measure of the desire of a group of people for trip making under a particular set of circumstances. The demand function expresses the number of trips or travel that will be demanded at each level of the various factors influencing travel demand. As the price of travel changes, the amount of trip making changes as well (Hendrickson and Wohl, 1984).

Figure 79 depicts a linear demand function for trip making between a given pair of origin and destination points, at a specific time of day and for a particular purpose, expressed by function (7.1) with respect to price of travel. At a price of pA, a volume qA of trips will be demanded. With a price increase to pB, traffic volume will decline to qB. The demand function can be used to estimate changes in volume only if the other components of user cost, such as travel time and socioeconomic conditions, remain constant. This demand function (or curve) assumes a particular level and distribution of income, population, and socioeconomic characteristics. It is an aggregate demand curve, representing the traffic volume demanded at different prices by a particular group or aggregate population, including travelers having high or low urgencies for trip making (Hendrickson and Wohl, 1984).

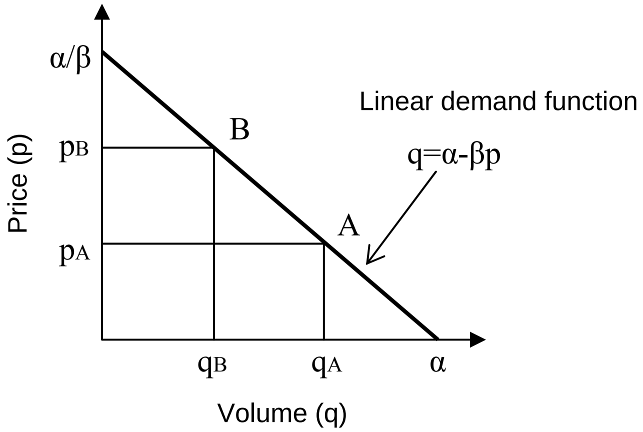

Figure 79. Demand function

$q = \alpha - \beta p$ (demand function with respect to price) (B.1)

where:

q : Quantity of trips demanded when the price is p
α and β : Constant demand parameters

The demand function (B.1) can be expressed by the following with respect to travel time and fares:

$q = \omega - \lambda t - \kappa f$ (B.2)

where:

ω, λ, and κ : Parameters
t : Travel time
f : Fare

Also, changes in population, income, or other socioeconomic characteristics could result in shifts or movement (i.e., increase or decrease) of the demand curve as function (B.3) depicts:

$q = f(p, SE)$ (B.3)

where:

q : Quantity of trips to be demanded when the trip price is p and with socioeconomic conditions SE

Public projects often produce goods that are not traded in markets. For example, highway projects provide highways, that is, non-tradable goods, to the public. Since we frequently encounter situations in which we cannot directly infer the demand function from market data like public projects, the following alternative methods listed in Table 36 are used.

Table 36. ALTERNATIVE METHODS FOR INFERRING DEMAND FUNCTION

Methods	Details
Hedonic price models	Identify the independent contribution of specific characteristics on price. • E.g., estimation of the value of life implicit in risk-wage trade-offs: how much people implicitly value their lives by seeing how much additional wage compensation they demand for working at riskier jobs. • If we observe people willing to take the riskier job (a 1/1000 greater risk of fatal injury per year) for an additional $2000 per year in wages, then we can infer that they are placing an implicit value on their (statistical) lives of $2000/(1/1000), or $2 million. The validity of our inference depends on the jobs' differing only in terms of risk and the workers fully understanding the risk.
Survey assessments (Contingent Valuation)	Ask a sample of people how much they would be willing to pay to obtain the benefits of public goods. • By comparing the demographic characteristics of the sample to those of the general population, an estimate of the aggregate willingness to pay for specific levels of public goods can be made. • Answers are sensitive to the particular wording of questions. • Nonrandom sampling designs or non-responses can lead to unrepresentative samples. • Respondents have limited attention spans. • Respondents often have difficulty putting hypothetical questions into meaningful contexts.
Activity surveys (Travel Cost Method)	Estimate the value of recreation sites from people's use patterns. • E.g., we could survey people who live various distances from a regional park about how frequently they visit it. We then would statistically relate the frequency of use to the travel costs and the demographic characteristics of the respondents. • These relationships enable us to estimate the population's demand schedule for park visits so that we can apply standard consumer surplus analysis.

Source: Weimer and Vining, 2004

User Cost Function

The user costs of a trip are usually estimated as a weighted linear combination of travel time components and monetary payments for a trip (Hendrickson and Wohl, 1984), such as:

$p = vt + f$ (B.4)

where:

p : Price or user cost of travel (in dollars)

t : Travel time
f : Fare or monetary payment
v : User time cost parameter and represents the unit value of travel time (value of time: in dollars per unit of time)

V, the unit value of travel time, can be measured by the willingness to pay a toll or higher parking fee in order to reduce trip time or walking time on a given trip. Given the various travel time components, monetary charges, and appropriate parameter values, the user cost of travel for a particular trip can be estimated by using function (B.4).

The dependence in function (B.4) needs to be addressed by price-volume functions, or relationships that express the user cost or price of travel on particular facilities as a function of its usage. To calculate price-volume relations, it is necessary to develop a mathematical expression (B.5) relating the travel time to different volume levels on a facility.

$$t = t_0 + \delta q \qquad \text{(B.5)}$$

where:

t : Average travel time for a usage level of q
t_0 : Travel time for low or near-zero volume levels on the facility
δ : Travel time congestion parameter for that facility

User cost or price-volume relation would be as follows:

$$\begin{aligned} p &= vt + f \\ &= v\,(t_0 + \delta q) + f \\ &= v\,t_0 + v\delta q + f \qquad \text{(B.6)} \end{aligned}$$

or

$$p = \tau + \xi q + f \qquad \text{(B.7)}$$

where:

p : User price at a usage level of q
f : Money expense
τ : Constant parameter representing the value of the minimum trip time
ξ : Parameter representing the joint effects of travel time increases and the unit time value (so that $\xi = v\delta$)

From equation (B.7), it is obvious that the user cost or price will be dependent both upon the level of usage, q, and the monetary charges, f, as Figure 80 shows.

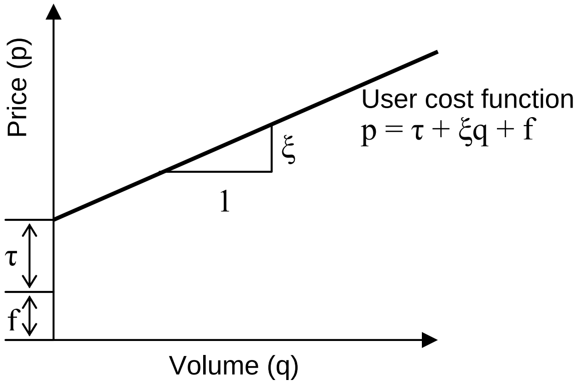

Figure 80**. User cost function**

Supply Function

A supply function depicts the dependent relationship between prices of a good or services to be provided and the quantity provided. The formula for a supply function is similar to that of a user cost function in equation (B.7), showing price-volume relationship as follows:

$p = a + bq$ (B.8)

where:

p : Price of a good or services at the number of units q

a and b : Parameters

The supply function focuses on supply side from the perspective of the transportation system's administrator or the system itself, while the user cost function focuses on user side from users' perspective.

Relationship among Demand, User Cost, and Supply Functions

Once we have a demand function and a user cost function or a supply function, we can obtain the volume of travel expected on a transportation system as well as the user cost of travel or average price from the intersection (i.e., equilibrium point) where those functions cross each other, qe and pe, as depicted in Figure 81.

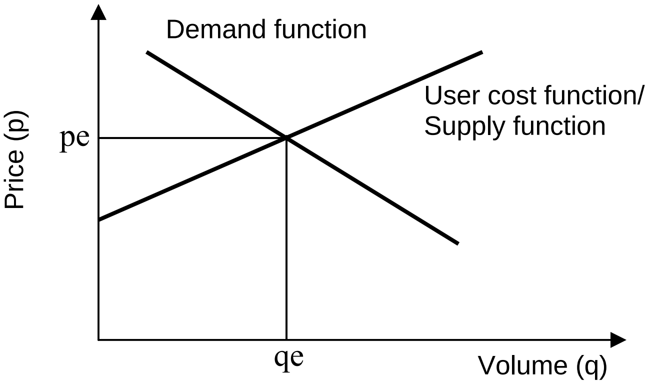

Figure 81**. Demand and cost functions**

Costs and Benefits

This part describes what kinds of costs and benefits are considered and how they are obtained.

Concept of Costs and Benefits

If we analyze transportation system investment, we need to think of what benefits and costs are produced by the investment. The investment may produce benefits including: 1) savings in user costs such as the personal travel time, effort, and hazard costs expended by the travelers for their trip making, 2) increase in profits of producer (i.e., agency) and reduction in operation and maintenance costs, 3) reduction in externalities such as air and noise pollution incurred by non-users, while costs include agency costs for a capital investment of a transportation system. Even though the benefits may be negative, that is, costs, we put the negative value into benefits if it does not belong to the costs for facility investment per se. The benefits take into account values added by the investment, while the costs are values of the investment. Table 37 summarizes the benefits and costs related to the transportation system investment.

Costs and Benefits Estimation

Benefits of new investments on a transportation system are derived from the aggregation of the individual charges or costs incurred by affected individuals or organizations. Costs and benefits in terms of user, producer, and non-user are described below.

Table 37. LIST OF BENEFITS AND COSTS OF SYSTEM INVESTMENT

Perspective	Benefits	Costs
User	Reduction in user costs: • Fixed vehicle ownership costs • Variable vehicle costs • Variable user travel time, effort, and hazard costs • Fixed costs that remain fixed and that do not change with increased usage of a facility. • Variable costs that vary or change with increased usage of a facility.	
Producer	Increase of profits (producer surplus) Reduction in operation and maintenance costs • Variable facility costs	Capital investment • Fixed (or non-separable with respect to the volume of usage) facility and social dislocation costs
Other	Reduction in external costs • Other costs (e.g., external air and noise pollution costs) • Include external costs that are imposed on others (especially nonusers) as a result of transport movement by users.	

Total User Costs and Consumer Surplus

The changes in total user costs and consumer surplus can be estimated by the total area under the demand curve (Hendrickson and Wohl, 1984). Figure 82 illustrates a demand function and consumer surplus. An individual will usually be willing to pay a little more than he/she was actually charged in order to get a little extra value. Let's assume Figure 82 shows the price-volume relationship of a highway. When the traffic volume is less than qB, a user (driver) can arrive earlier at his/her destination. Hence, he/she is willing to pay more than price pB. The amount of price based on the user's willingness to pay with respect to the traffic volume will draw the demand function. Now the price is pB. Travel benefits, user costs, and net user benefits at price pB are:

- Travel benefits at price pB = value derived from qB trips = □BCOF
- User costs at price pB = user payments for qB trips = □BDOF
- Net user benefits at price pB = △BCD = consumers' surpluses at price pB = NUB_B

Later, the price has been changed from pB to pA. At the time, traffic volume has increased from qB to qA because the number of users, qA-qB, were induced by the price reduction. Travel benefits, user costs, and net user benefits at price pA are:

- Travel benefits at price pA = value derived from qA trips = □ACOG
- User costs at price pA = user payments for qA trips = □AEOG

- Net user benefits at price pA = △ACE = consumers surpluses at price pA = NUB_A

How much can users benefit from the price reduction? We can calculate the change in net user benefits (ΔNUB) from the change in price as follows:

- Change in net user benefits from price reduction = □ABDE = change in consumers' surpluses = $NUB_A - NUB_B$

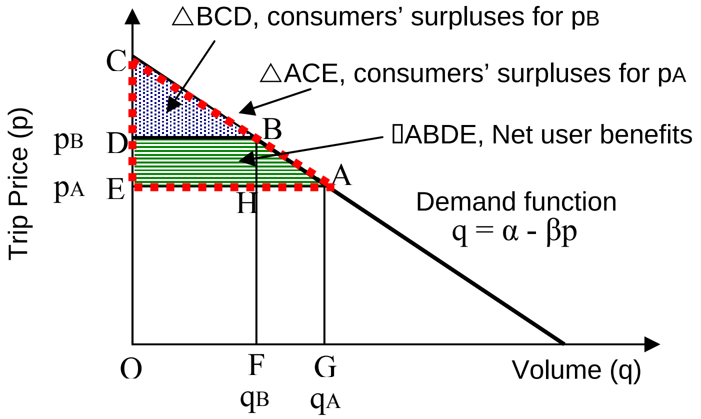

Figure 82**. Demand function and consumer surplus**

Producer Surplus

In addition to the net user benefits, there are also benefits from the supply side. While consumer surplus (i.e., user benefits) accrues for users from a fall in product prices, benefits accrue for producers from a rise in prices. Figure 83 represents a supply function indicating the number of units of a good or service that a producer offers at each of various prices. If we assume a producer provides highway services, the number of units represents that of through traffic on the highway. The producer offers a total quantity qB at price pB. As price increases, the producer offers successively greater quantities, yielding an upward-sloping supply function. Suppose the price increases to pA so that the quantity supplied is qA. Then the total cost of producing qA is the area □AGOE. The total revenue to the producer, however, equals price times quantity, given by the area of rectangle □AGOC. The difference between total revenue and total cost equals the producer surplus accruing to the producer, measured by the total shaded area inscribed by △AEC (Weimer and Vining, 2004).

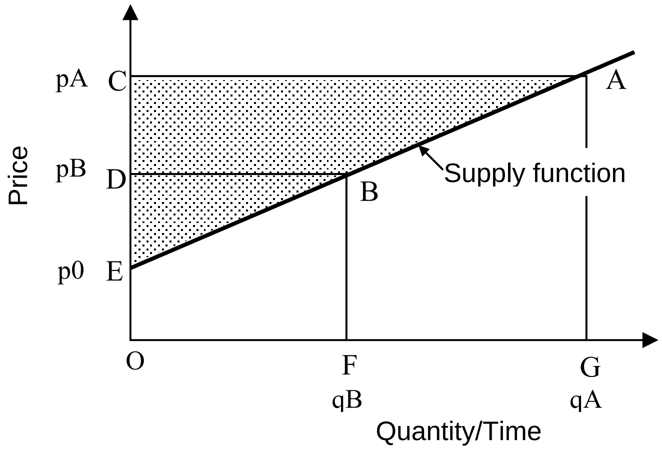

Figure 83**. Supply function and producer surplus**

External Costs

External benefits include a reduction in environmental costs, which are incurred by non-users. The environmental costs are the value of safeguards that maintain our (non-users') environment such as air, noise, vibration, water, and aesthetics. Table 38 shows environmental problems caused by transportation projects. Most BCA studies related to transportation usually take into account air pollution as an externality, using the results from various studies. Although the techniques in Table 36 may be able to estimate costs of the safeguards for noise, vibration, water, and aesthetics, it is difficult to obtain absolute values due to the nature of the techniques that are easily affected by survey methods and subjects of survey. To evaluate transportation projects using BCA, however, incorporating them into external benefits is required.

Now, we focus on air pollution to understand the impact of external costs incurred by highway investment. Figure 84 shows the conceptual relationship between VMT and emission damage cost per VMT[19]. Suppose that there are VMT, qB at the damage cost, pB. The total damage cost can be calculated by qB multiplying pB, which is □BDOE. After the highway investment, VMT may increase to qA because of a better driving environment. For example, a widening treatment provides additional road capacity and thus increases speed and VMT. At this time, the total damage cost is □ACOF. The (negative) benefits of externality are the difference between □ACOF and □BDOE.

Next, let's assume that a mitigation measure is implemented as shown in Figure 85. The mitigation measure makes the original VMT-cost curve at qA move downward from A to A' because the measure alleviates emission damage. Thus the emission damage cost per VMT is reduced from pA to pA'. At this time, the area of rectangle □ AA'DC (= □AFOC – □A'FOD) is equal to the reduction of the total damage cost produced by the mitigation measure.

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[19] HERS-ST uses emission damage costs per VMT by vehicle class and average travel speed. Since the investment may affect traffic volume, vehicle class and speed, HERT-ST forecasts them and then estimate the emission damage costs (U.S. DOT and FHWA, 2005).

Table 38. ENVIRONMENTAL PROBLEMS AND CAUSED BY TRANSPORTATION PROJECTS

Category		Short-Term	Long-Term
Air	Direct	Emissions caused by construction vehicles and asphalt plant for M&R Incremental emissions from travelers' vehicles around the activity site due to detour and slow down	Emission caused by travelers' vehicles
	Indirect	Emissions caused by power plant generating electricity, fuel plant refining vehicle fuel, and other activities providing goods and services related to the activity.	Chemical production, chemical loss, and deposition from chemical reactions among emissions
Noise	Direct	Noise caused by construction vehicles, construction, and asphalt plant	Noise caused by travelers' vehicles
Vibration	Direct	Vibration caused by construction vehicles and construction itself	Vibration caused by increased traffic
Water	Direct	Runoff caused by construction	
Aesthetics	Direct	Aesthetic problem caused by construction site	Aesthetic problem caused by new facility (e.g., widened lane disturbs neighbors' view)

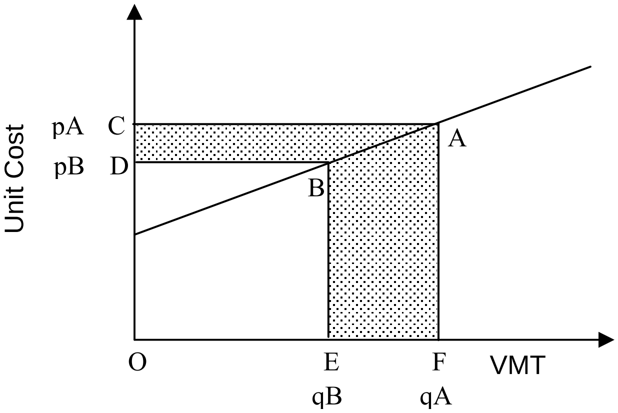

Figure 84. Conceptual relationship between VMT and costs

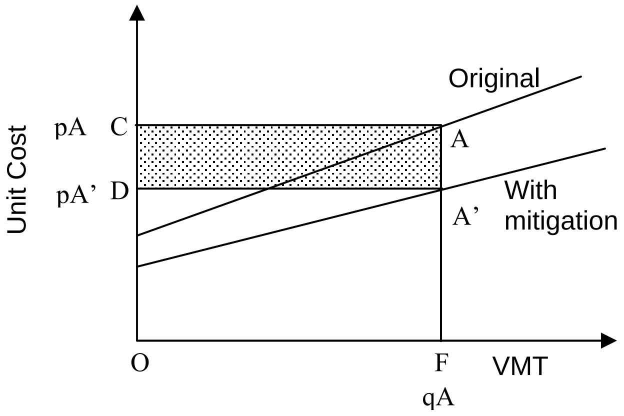

Figure 85. Effect of mitigation

Application

The previous subsections presented the foundations of BCA such as principles and elements to understand BCA. This part discusses how BCA can be applied to quantifying benefits of implementation of AMS, with particular emphasis on pavement management. Once we define the benefits and costs, we need to estimate benefits and costs, which is the most important and complex task. The following parts explain how to conduct this task.

User Benefits

Figure 86 shows the relationship of user benefits. Suppose that currently there is traffic volume, qB, on a road network. At the time, drivers incur trip price, pB, including vehicle operating cost, safety cost, and travel time cost, and there is a user surplus △BCD. After implementing PMS, it is assumed that traffic volume, qB, will change to qA because PMS allows transportation agencies to provide a better driving environment using appropriate M&R treatments (e.g., routine and periodical maintenance, resurfacing, reconstruction, and widening), and then this better environment will reduce users’ trip price from pB to pA. Archondo-Callao (2004) shows that vehicle operating costs per unit decrease as driving environment, in terms of the relationship between road/pavement quality and car speed, improves. A user surplus at the trip price, pA, is △ACE. In reality, traffic volume may be not be so sensitive with respect to driving environment because our lives already depend on vehicles and because driving conditions are relatively acceptable although we experience potholes and traffic congestion. If we apply the outputs of PMS such as widening and upgrading from unpaved surface to paved surface, we may be able to observe the improvement of traffic flow and traffic volume increase.

Comparing the user surpluses between at pA and pB, we can obtain net user benefits from trip price reduction. □BDEH represents user cost savings in traffic volume qB, while △ABH represents incremental user surplus produced by the induced traffic volume, qA-qB, due to the price reduction. These areas are considered as user benefits.

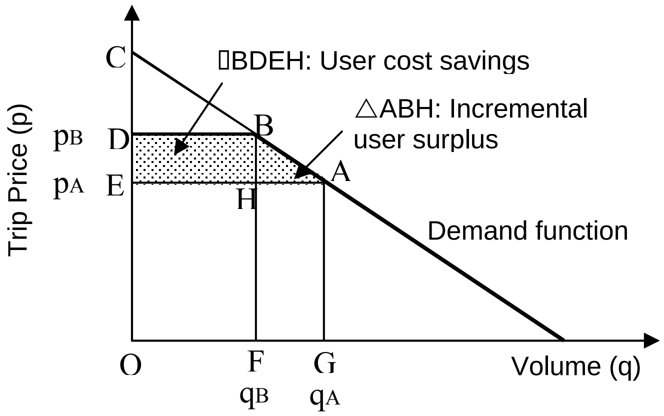

Figure 86. User benefits

A demand function consists of various user costs such as travel time, vehicle operation, and safety with respect to traffic volume. In order to build the function, we can estimate each cost using empirical data and aggregate the costs at specific traffic volume. Then, elasticity[20] is applied to forecast how much traffic is induced by the change of user costs. For example, HERS-ST employs various models consisting of a travel time cost model, a vehicle operating cost model, and a safety cost model, with respect to prices or costs. Also, there are sub-models such as a pavement deterioration model and a speed model to be integrated into the models above. Using the models, HERS-ST finally estimates user costs while taking into account elasticity (U.S.DOT and FHWA, 2005). Hence, for estimating the user benefits, we can use a function of the benefit estimation in the existing PMS[21] as described in the example.

Agency Benefits

To explain how agency benefits can be estimated, we use a toll road. The relationship between traffic volume and the toll are used to estimate agency benefits from the perspective of a transportation agency that is in charge of a toll road as illustrated in Figure 87. Suppose that there is traffic volume, qB, at the toll price pB before PMS implementation. The agency's total revenue is □BCOG, including costs for operation and M&R, □BEOG and profits (i.e., producer surplus), △BCE. After the agency implements PMS, the supply function expressed by marginal cost may move downward due to M&R cost reduction, and then the toll price can be reduced until the price pJ. The cost reduction can be realized if the traffic volume and road length are under the same condition as before PMS implementation. The profits, △IJF, are kept at the same amount as △BCE, profits at the price pB, while the costs for operation and M&R decrease to □IFOG. Hence, the difference between □BEOG and □IFOG represents agency benefits.

The traffic volume may increase to qA because of the reduction of toll price and better driving environment after PMS implementation. At the traffic volume qA, the agency needs to increase the toll price to pA in order to maintain the road at the same condition despite the traffic

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[20] (Direct demand) Elasticity measures the change in demand for a good or service with respect to a variable that is directly related to that good or service.

[21] Strictly speaking, HERS-ST is not PMS because it does not provide engineering pavement options. Rather, HERT-ST is one AMS, which provides optimal budget allocation scenarios including strategic investment options.

increase. The agency will obtain revenue, □ADOH, including costs for operation and M&R, □AFOH, and profits, △ADF. The agency benefits compared to that before PMS can be derived from the differences of the costs for operation and M&R (i.e., □BEOG and □ADOH) and of the profits (i.e., △BCE and △ADF).

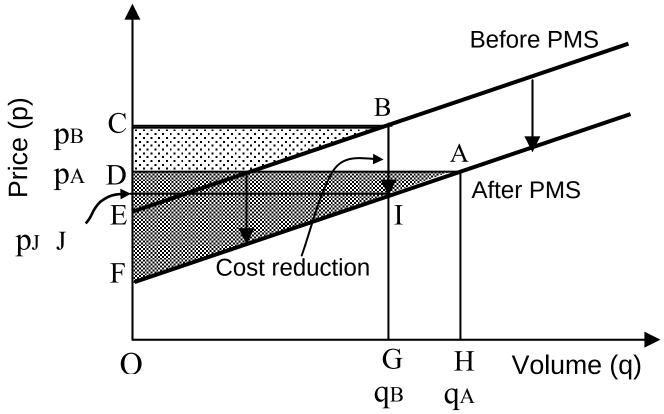

Figure 87. Agency benefits

The example indicates the need to build supply functions for before PMS implementation (or without PMS implementation) and after PMS implementation (or with PMS implementation). It may be possible to build these functions if there are data available regarding traffic volume and toll price for years before and after PMS implementation. However, the tolls are usually static with respect to traffic volume unless the toll road uses a dynamic pricing scheme. Hence, it is difficult to use this process to calculate agency benefits.

In addition, the subjects to quantify benefits of PMS implementation are not only toll roads but also non-toll roads. For non-toll roads, there is no measure such as toll price from users' perspective in conjunction with traffic volume because they are free. Road dedicated tax may be an approximate measure, but it is also not dynamic with respect to traffic volume. We need appropriate methods to estimate agency benefits.

HERS-ST provides a good solution to estimate the agency benefits in terms of a reduction of M&R costs. Based on pavement condition using PSR (Pavement Service Rating) with respect to the pavement structural number, HERS-ST addresses marginal M&R costs per lane-mile for flexible pavements, for example, when PSR drops from 4.5 to 4.0. Also, HERS-ST recognizes the change in usage based on price elasticity (U.S.DOT and FHWA, 2005). Using the costs for before and after PMS implementation and the usage, we can estimate agency benefits although we need to adjust pavement condition measures when we use IRI (International Roughness Index) rather than PSR. However, the costs may not completely reflect the subject at hand because they are historical costs derived from other projects in the nation.

External Benefits

PMS implementation may improve the driving environment by providing appropriate M&R treatments. The improvement affects traffic volume, vehicle class, and speed, and thus externalities such as air and noise. As described above, the relationship between VMT and damage costs in Figure 84 is applicable to the externalities. For estimation of external benefits, a function in HERS-ST can be used although the function offers only a limited estimate of benefits from improvements in air quality.

Benefits

Now, we focus on AMS implementation. The benefits realized from implementing AMS (Haas et al., 1994; Litzka et al., 2000; Sztraka, 2001; Cowe Falls and Tighe, 2004; Smadi, 2004) can be classified in terms of nine categories, created by Organisation for Economic Co-operation and Development (OECD, 2000), and four different stakeholders' perspectives, identified by Haas et al. (1994). These benefits are summarized in Table 39. Each level has different benefits depending on the objectives of the stakeholder groups.

The objective of elected representatives is to guide civil systems, including infrastructure, in the right direction by monitoring agencies' performance. Since AMS help agencies to conduct business efficiently, the elected representatives receive strategic benefits through the justification of M&R programs and assurance of the best expenditure of funds.

Within agencies, there are two levels of implementation of AMS: tactical level of top management and operational level at technical levels. On one hand, top management has to not only lead agencies to their goals determined by a strategic plan and public comments, but must also maximize their assets' performance while minimize their expenditure. On the other hand, the objective of technical people is to maintain, upgrade, and operate physical assets using expert skills and knowledge. AMS implementation helps agencies achieve these objectives. The indirect effects are recognized in the improvement of communication and knowledge in various administrative and operating elements.

Lastly, the public can be divided into two groups: users and non-users. Road users use infrastructure as the built environment that supports their business and life without any risks and costs. They may be satisfied with reliable, improved assets (e.g., safer and smoother road surfaces) maintained through the decision support provided by AMS. Also, they will have benefits from savings in user costs, consisting of travel time, vehicle operation, and safety, thanks to the smooth surfaces that allow increasing driving speed, for example. Non-users want to maintain a good living environment (e.g., less air pollution and noise coming from highways). Since AMS will provide better driving conditions as mentioned above, non-users may appreciate reduced air pollution, noise, and annoyance due to traffic congestion that is caused by deteriorated and disordered infrastructure. However, we may have a completely different picture. Smoother surfaces allow road users to drive faster, thus causing serious traffic accidents and higher emission level and therefore increasing safety and external costs. Otherwise, these surfaces may induce additional traffic and aggravate traffic congestion, thus increasing travel time, emissions and noise. Furthermore, people may suffer from delay, emission, and noise along M&R sections where frequent preventive M&R programs recommended by AMS are incurred. Due to the uncertainties of people's behavior and perception corresponding to the improved assets, it is difficult to quantify the costs for the public.

As we can see in Table 39, benefits have two types: qualitative benefits and quantitative benefits. On the one hand, qualitative benefits imply improvements in stakeholders' capability and environment, which cannot be monetized. On the other hand, quantitative benefits are expressed by improvements (called savings and reduction) in costs, monetized value, such as agency costs and user costs.

Those benefits are not produced as soon as AMS are implemented, but are accrued through the usage of AMS in agencies' business. Although it is difficult to articulate when the benefits are produced by AMS, many agencies have recognized that the existence of the benefits (Hendren, 2005). However, there is no rule of thumb to quantify the benefits. Although several researchers (Hudson et al., 2001; Cowe Falls and Tighe, 2004; Smadi, 2004) have quantified them, the methods used are inconsistent and have limitations in counting whole benefits coming from AMS, especially qualitative benefits such as communication, satisfaction, and externalities. Hence, agencies have introduced a variety of performance outcome measures[22] to measure the benefits in terms of 3Es: **efficacy** showing whether AMS work or not; **effectiveness** identifying the degree to which AMS achieve the agency's goal in asset management; and **efficiency** identifying minimum use of resources using the ratio of output or outcome (i.e., performance) to input (i.e., resources) of AMS (Checkland, 1999).

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[22] Examples of indicators: nominal (yes, no); ordinal (first, last); interval (0-10); ratio (0-100%)

Table 39. BENEFITS OF AMS IMPLEMENTATION

Category	Elected Representatives (Strategic Level)	Top Management (Tactical Level)	Technical Level People (Operational Level)	Public (User & Non-user Level)
Budget allocation process	Assurance of best expenditure of funds	Improved allocation process within a program area Assurance of best use of available budget Providing a basis for allocating funds among different districts or agencies Justifying capital spending and maintenance programs to the elected council or legislature Use of standard accounting concepts and terms to provide understandable information to the decision makers		
Asset Inventory		Defining the 'management fee' as a percentage of the spending on capital and maintenance work	Ability to build more accurate information Ability to track the performance of treatment strategies Ability of a wide range of staff to query database Integrated harmonized database (consistent data) Provision of up-to-date accurate information on the condition	
Road performance	Improved road performance			Satisfaction of using improved assets Improved road serviceability Savings in user costs (travel time, vehicle operation, and safety) Reduction of environmental impacts (air, noise, and annoyance)
		Savings in agency costs (construction and M&R)		

Table 39. (Continued) BENEFITS OF AMS IMPLEMENTATION

Category	Elected Representatives (Strategic Level)	Top Management (Tactical Level)	Technical Level People (Operational Level)	Public (User & Non-user Level)
Management tools	Realization of the magnitude of the investment that the agency has a better chance of making correct decisions on spending funds			
	Actual operation of the system being able to defend/justify programs of maintenance and rehabilitation Reduction of pressure (from constituents) to make arbitrary program modifications Objective answers to the implications of: lower levels of funding lower standards	Common definitions and standards for maintenance and rehabilitation Economic modeling Provision of an estimate of the economic effect of spending scenarios (scenario analysis) Ability to manage assets on an economic basis (cost-benefit, engineering economics) Prioritization of maintenance needs on the basis of future costs rather than current condition (life cycle cost) Selection of the best maintenance and rehabilitation measures or strategies		
		Comprehensive, comparative assessment of: Current status of the network Expected future status Objectively based answers to: What level of funding is required to keep the current status The implications of greater or lesser budgets The implications of deferred work The implications of lower standards	Satisfaction of providing best value for available funds Capability of assessing the implications of: Less funds, lower standards Capability of making the case for higher standards Capability of quantifying the assessment of the condition Improved credibility of decision-making process when dealing with top management Improved quality of performance curves (i.e., deterioration models) due to data collection and processing	

Table 39. (Continued) BENEFITS OF AMS IMPLEMENTATION

<table>
<tr><th>Category</th><th>Elected Representatives (Strategic Level)</th><th>Top Management (Tactical Level)</th><th>Technical Level People (Operational Level)</th><th>Public (User & Non-user Level)</th></tr>
<tr><td>Staff development</td><td>Improved knowledge of pavement conditions and needs</td><td>Improved knowledge of pavement conditions and needs</td><td>Improved recognition of various administrative and operating elements of the organization
Broad multi-disciplinary knowledge
Provision of access to accurate data, state-of-art Information Technology, and analysis tools needed for efficient management
Improved knowledge of pavement conditions and needs
Upgrade skills</td><td></td></tr>
<tr><td rowspan="2">Communication</td><td rowspan="2"></td><td colspan="2">Improved communication
Common benchmarks
Improved internal and external communications
Adoption of accounting practices</td><td rowspan="2">Understanding of agencies business via performance monitoring reports</td></tr>
<tr><td>Ability to defer lobbying pressures from special interest groups</td><td>Improved communication with design, construction, maintenance, planning, and research
Enabling front line staff to become more involved in the decision making process</td></tr>
<tr><td>Application of technology</td><td></td><td></td><td>Increased awareness of available technology and how to use it
Better utilization of manpower
Time saving in evaluating development alternatives</td><td></td></tr>
</table>

Costs

Compared to the benefits, costs for the implementation of AMS are easier to quantify as summarized in Table 40 (Haas et al., 1994; Cowe Falls and Tighe, 2004). The direct costs are of data acquisition, system software and hardware installment, and system development and operation at agencies. Also, there are indirect costs such as indirect labor, indirect material, and fixed costs. In addition, there would be costs for the public due to the improved assets maintained through the decision support provided by AMS.

Table 40. COSTS OF AMS IMPLEMENTATION

Category	Top Management (Tactical Level)	Technical Level People (Operational Level)
Data acquisition	• Data collection	• Data collection, processing, storage and analysis
Management system	• Software development /acquisition and installing the system • Computer hardware, staff • Operating costs of the system	
Others	• Organizational changes • Staffing	• Making changes in procedures • Extra time and effort to upgrade skills and learn new procedures • Training and education costs

Methods to Quantify Benefits

Among the six critical barriers to asset management in the U.S. addressed in Section 1.2, costs can be addressed by demonstrating that the benefits of AMS implementation exceed these costs. This research develops a generic methodology for quantifying benefits derived from implementation of AMS. This section summarizes analysis methods to quantify and analyze the benefits of implementations of both PMS as one of AMS and other applications including Transit and Intelligent Transportation Systems (ITS) derived from six research papers. The details of the papers are described in APPENDIX B. As shown in Figure 88, the methods are divided into four parts: before and after analysis, regression analysis, and benefit-cost analysis. Although the three types of methods are mutually exclusive to each other, the three overlap and represent joint methods since two reviewed research papers utilize more than one method. Each method is explained in light of the contexts of the reviewed research papers as follows.

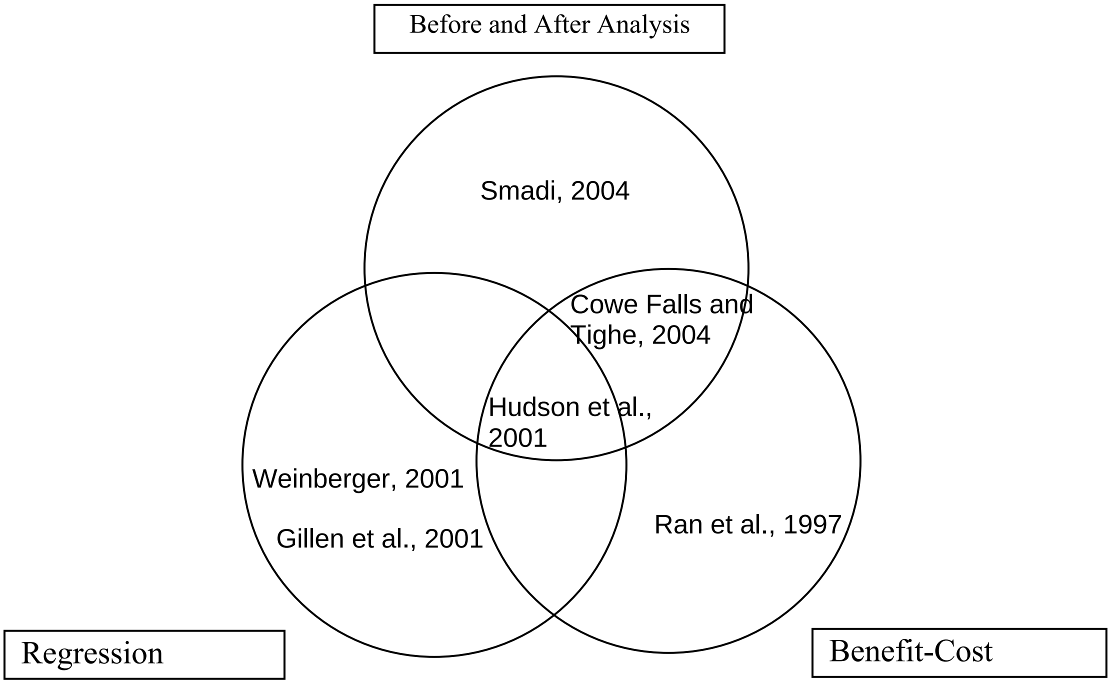


Figure 88. Research based on benefits quantification methodology

Before and After Analysis

Before and after analysis compares agencies' performance such as asset condition, benefits, and costs before and after PMS implementation. This analysis is based on the assumption that asset performance after implementation is better than that before implementation. For example, Smadi (2004) observed differences between actual Pavement Condition Index (PCI) derived from survey and virtual PCI calculated by PMS during before and after PMS implementation phases. Then, he compared the differences to see how close actual PCI gets to virtual PCI. Also, he estimated unit monetary value for one PCI from PCI difference and budget difference between the actual work program and the virtual program recommended by PMS at the before phase and applied the value to the after phase to calculate budget difference at the time. The concept is that if the PCI difference becomes smaller between the virtual and actual after PMS implementation, the agencies' pavement program has been improved due to the effect of PMS. He concluded that the pavement program has been improved and Iowa DOT gained benefit equivalent to $5 million over a 5-year period after PMS implementation.

Cowe Falls and Tighe (2004) also used before and after analysis in their benefit-cost analysis. They collected data on the availability of rehabilitation funds, Pavement Quality Index (PQI), network length, and vehicle kilometers traveled (VKT), for both the before and after PMS implementation phases. Then they estimated savings on replacement cost of pavement (i.e., agency benefit) and vehicle operating costs (i.e., user benefit) under the condition where the rehabilitation costs and VKT are consistent between the two phases. Using the savings as benefits, PMS development and operating costs, and survey equipment costs in benefit-cost analysis later, they finally calculated a benefit-cost ratio to demonstrate that benefits of PMS implementation exceed its costs. They found that pavement asset value for Alberta

Transportation increased $550 million and PQI increased 0.5 for the entire road network after PMS implementation.

Hudson et al. (2001) also employed before and after analysis using regression models, consisting of roughness index and pavement age, to capture how pavement lasts longer due to the effect of PMS. They showed that pavements last 2.0 years or 13.5% longer on the average due to the advent of pavement management and the development of PMS before reaching a tolerable roughness level. The increase of pavement life was used as a benefit, that is, one savings in agency costs in benefit-cost analysis.

Regression Analysis

Regression analysis models the relationships among variables and illustrates the degree of independent variables' influences on a dependent variable by coefficients. There are two types of regression analysis in the literatures as follows:

Estimation of Benefit and Cost Attributes

One of these is a regression model to estimate benefit and cost attributes which represent the degree of benefits and costs of intervention. For example, Hudson et al. (2001) built regression models showing the relationship between roughness and age for before and after PMS implementation phases. Then, as addressed above, they found that pavements last 2.9 years or 13.5 % longer due to the effect of PMS.

Also, Weinberger (2001) used regression analysis to explain how consumers value light rail transit (LRT) in terms of the value of real property. Her model includes distance to transit as an independent variable to see how much the distance affects property lease price. If the coefficient of the distance is positive, LRT makes the price increase. The increase can be thought as benefit of LRT in terms of real estate companies, people living there, and local government. The result showed that, properties that lie within 0.8 km of a light rail station command higher lease rates than other properties after controlling for variables such as length and type of lease, building improvements, and so on.

Assessment of Productivity

The other type is a regression model to assess productivity of intervention. Gillen et al. (2001) measured the impact of Advanced Vehicle Location (AVL), one ITS application, using total factor productivity (TFP) for public transit over a period of time. They determined that "*TFP aggregates outputs on the basis of their revenue contribution and inputs on the basis of their relative importance to total costs in order to calculate the overall transit agency productivity as a function of these quantities*." They used multiple regression models using several independent time series variables including an AVL dummy variable so that they could address the impact of AVL in TFP, the dependent variable. They revealed which variables have significant influence and the amount of influence on productivity performance for public transit systems, and then they addressed the benefits of AVL, that is, the increase of productivity using the coefficient of the AVL dummy variable. In the analysis, they considered three TFP measures: total passenger trips, total passenger miles, and total vehicle revenue miles.

Benefit-Cost Analysis

BCA is used to see efficiency of a program, that is, whether benefits produced by a program exceed its costs. Ran et al. (1997) simulated six scenarios which have different automated highway system (AHS) corridor types and AHS vehicle percentages using benefit-cost analysis in order to prioritize them based on net benefit. They calculated time saving for benefit, and preparation costs of roadway, AHS infrastructure and in-vehicle equipment for costs over 20 years by applying a discount rate. The scenario which has largest net benefit is most preferable.

Although BCA is usually used to prioritize alternatives including do-nothing for project evaluation, it is used to verify a project's efficiency as well. If the efficiency is verified by the analysis, the project is eligible to be executed; otherwise, it should be terminated. Cowe Falls and Tighe (2004) verified PMS implementation. They used savings in agency and user costs between before and after PMS implementation phases for benefits; and PMS development and operating costs, and survey equipment costs during before PMS implementation phase for costs, in order to calculate a benefit-cost ratio. They found that the ratio is larger than 82, and then some savings within the expenditure of $235 million in rehabilitation and new construction would have occurred from PMS implementation.

Hudson et al. (2001) also calculated a benefit-cost ratio, using savings in agency costs for benefits, PMS development, operation, and equipment costs from before PMS implementation phase to after PMS implementation phase. The result showed that a benefit-cost ratio is 33 and there would be a saving of $270 million using minimum confidence interval values.

In summary, the three analysis methods are reviewed to understand how to quantify benefits of implementation of both PMS and other applications. Throughout the literature review, it is recognized that each method has the pros and cons listed in Table 41.

Summary of Literature Review and Background

This appendix reviewed the fundamental principles of BCA and examples from the literature of how these principles have been applied. In reality, the concepts of BCA are difficult to apply as users do not experience a real market. The appendix also reviewed methods to quantify benefits. Drawing on this review, Chapter 3 develops a methodology for evaluating AMS implementation.

Table 41. PROS AND CONS OF BENEFIT QUANTIFYING METHODS

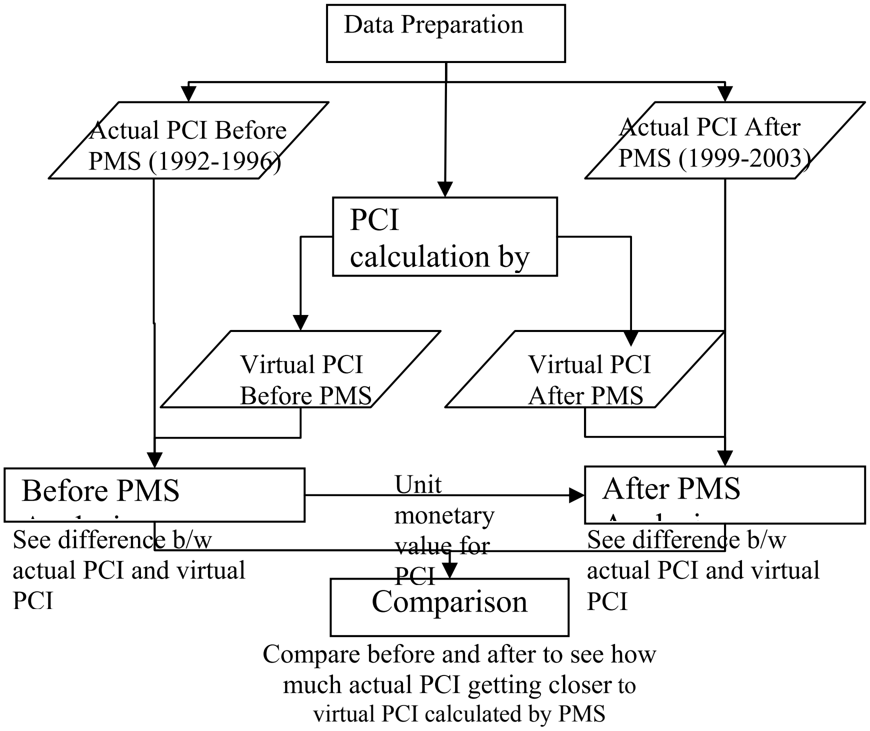
Methods	Pros	Cons
Before and After	• Can use a common measurement to discuss benefit of PMS implementation such as increase of PCI. • Require minimal data because it focuses on one performance dimension.	• Cannot consider changes (e.g., traffic, budget, network length, etc.), when addressing benefits (e.g., increase of PCI) simultaneously. It is difficult to specify how much PMS contributes to the increase of PCI without controlling those variables. • When using PCI, researchers tried to show the benefits (i.e., increase of PCI) using monetary value. However, calculating monetary value is not straightforward because each PCI has different monetary value. For example, lower PCI has larger monetary value; higher PCI has smaller monetary value. • In order to calculate monetary value from PCI or pavement life, researchers used those average values for entire network. The value, however, may cause aggregation bias. Using condition index expressed by small range scale (e.g., 0-10), the bias produces significant difference in the result of monetary value.
Regression	• Specify what kind of and how much independent variables significantly influence dependent variable. If use a dummy variable indicating that PMS is used, it can address the degree of PMS effect on dependent variable. • Can consider various changes which cannot be incorporated into before and after analysis.	• Require a number of variables to show the pattern of relationship existing among variables. • Need to determine appropriate dependent variable as a measure of benefits of PMS implementation. • Difficult to conclude that there is the cause and effect relationship between the two because the coefficients are derived from the pattern of relationship, although coefficients of independent variables show significant relationship with dependent variable. Hence, it is required to interpret the relationship based on subjective interpretation or refer other research addressing the relationship.
Benefit-Cost	• Show analysis result using monetary value, thus being able to understand benefits easily. • Address how much benefits exceed costs with net benefit. • Consider benefits and costs in terms of various standings such as agency, user, and non-user.	• No consistent manner to calculate benefits and costs. The definition of benefits and costs and those calculation methods are different from each other. • Cannot control change of traffic, budget, network length, and so on. • Need to decide appropriate analysis time horizon, since it is assumed that benefits and costs accrue over years. • Cannot count all benefits and costs using monetary value. The result of this method may reflect only a part of them. • Difficult to quantify qualitative benefits. Although there is contingency valuation method to quantify them, it is cumbersome and difficult to reflect people’s real value.

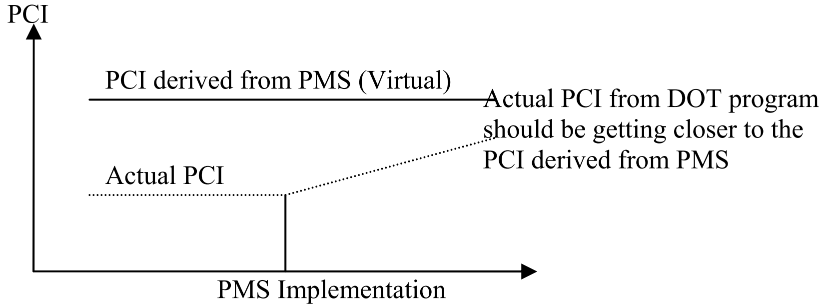
APPENDIX B. LITERATURE REVIEW: APPLICATIONS

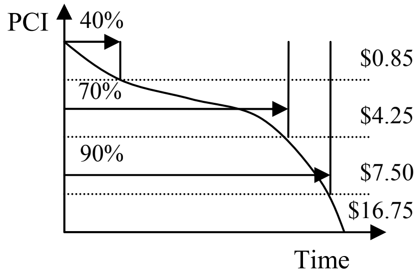
This appendix documents six research papers related to methods to quantify and analyze the benefits of various applications including PMS, transit systems, and ITS, which are addressed in APPENDIX A. Those papers are summarized in the following tables in terms of research strategy, data, model, results, and pros and cons.

Category: pavement; Type: quantitative

Title	Quantifying the Benefits of Pavement Management
Author(s)	Smadi, O, Research Scientist, Iowa State University, Ames, Iowa
Publisher	5th International Pavement Management, Seattle, 2001
Abstract	Pavement management systems (PMS) have been in operation since the early 1970s with varied success in full implementation. Pavement management engineers and maintenance managers understand the value and benefits resulting from the implementation of a PMS. When it comes to decision makers and top-level management, the picture is different. They are interested in benefits that can be translated into monetary values ($) rather than the regular benefits mentioned in the literature. This paper describes the authors attempt to fill in the benefits determination gap and presents a process that can be utilized to quantify benefits. The paper considers the Iowa Department of Transportation (Iowa DOT) PMS implementation as a case study. The Iowa DOT implemented a PMS in 1998 after an extensive period of evaluation of different tools to conduct pavement management. The Iowa DOT selected dTIMS™ (Deighton Total Infrastructure Management System) as the pavement management software. To quantify the benefits for implementing a PMS, the results form the PMS were compared against the construction program that the Iowa DOT implemented 5 years before PMS existed and 5 years after on the interstate system (2650 2-lane KM). The before PMS comparison was completed in 1997 and the difference between the recommendations from the PMS and the IDOT program was a 3.5% increase in pavement condition (2.64 PCI points). Using the PMS, to achieve a 3.5% increase in condition require an additional investment of $12.5 million over 5 years. When the after analysis was conducted, the difference in condition was 2% (1.45 PCI points). This is equivalent to an additional investment of $7 million over 5 years. The difference between the two comparisons is equal to the benefits derived from implementing the pavement management system. The paper will show the procedure used, the data requirements, and the data analysis.
Key Words	Pavement Management System, Iowa DOT, before and after comparison, PCI

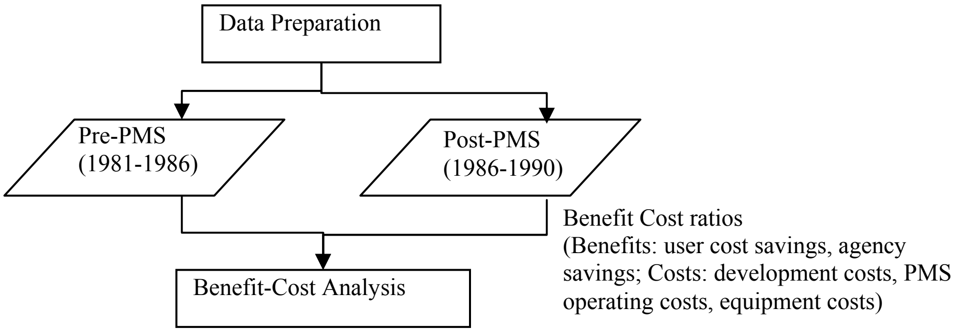
<table>
<tr><td>Research Strategy</td><td>
</td></tr>
<tr><td>Data Used</td><td>The pavement condition information, the implemented construction program for the Iowa DOT interstate network, and the pavement management parameters in PMS including prediction curves, treatment strategies, treatment costs and treatment benefits.</td></tr>
<tr><td>Model</td><td>Before PMS Analysis (1992-1996)
<table>
<tr><th>Category</th><th>PCI</th><th>Budget</th></tr>
<tr><td>PMS recommendations (virtual)</td><td>76.43</td><td>$ 162.5 million</td></tr>
<tr><td>Iowa DOT program (actual)</td><td>73.79</td><td>$ 175 million</td></tr>
<tr><td>Difference</td><td>2.64</td><td>$12.5 million</td></tr>
</table>
Unit monetary value for one PCI = $12.5 million/2.64 PCI = <u>$5 million/PCI</u>
After PMS Analysis (1999-2003)
<table>
<tr><th>Category</th><th>PCI</th><th>Budget</th></tr>
<tr><td>PMS recommendations (virtual)</td><td>73.08</td><td></td></tr>
<tr><td>Iowa DOT program (actual)</td><td>71.63</td><td></td></tr>
<tr><td>Difference</td><td>1.45</td><td>$7.5 million
(=$5 mil.*1.45 PCI)</td></tr>
</table>
If the difference gets smaller between the virtual and the actual after PMS implementation, it can be said that the Iowa DOT program has been improved due to the effect of the PMS. The concept is depicted below.</td></tr>
</table>

	
Result	• The before PMS analysis showed a more substantial increase in investment to achieve the same condition ($12.5 million) as the PCI derived from the PMS compared to the after PMS analysis ($7.5 million). • There was a difference of $5 million between the before and after analysis. • Indicate the monetary benefits resulting from the implementation of the pavement management system. • The $5 million is spread over a 5-year period making the annual benefit equal to about $1 million. • Compared to the cost of implementing the PMS for the interstate system, the benefits far outweigh the costs. • The resulting average network condition from the PMS matched very well with the actual condition data collected throughout the two analysis periods. • Confirm the accuracy of the performance parameters developed for the interstate system. • The projects selected by the Iowa DOT matched very closely with the recommendations from the PMS.
Pros	• PCI is a good measurement to discuss the benefit of implementation of PMS because many agencies hold PCI records. • This model does not require a variety of data to quantify the benefits.
Cons	• This model does not address traffic and budget constraints. o If traffic volume decreased and/or budget increased during the time period after PMS implementation, the actual PCI would get closer to the virtual PCI. o What if the actual budget is less than the selected budget of the PMS? It is possible the actual budget is less than the selected budget due to budget constraint. • If the difference between the actual and the virtual is very small, this method cannot justify the benefits of implementing a PMS due to a lack of sensitiveness. • It is required to address why the difference between the actual and the virtual occurred after PMS implementation. Policy changes? Budget constraint?
Others	• This model addresses how much the Iowa DOT's decision has followed the PMS recommendation. It does not address how much the Iowa DOT's pavement has been improved due to the PMS directly. • Since each PCI has different monetary value, the unit monetary value for PCI cannot be applied to the after PMS analysis directly. Lower PCI has larger monetary value based on the figure below.

	PCI 40% 70% 90% $0.85 $4.25 $7.50 $16.75 Time

APPENDIX B. METHODS (continued)

Category: pavement; Type: quantitative

<table>
<tr><td>Title</td><td>Analyzing Longitudinal Data to Demonstrate the Costs and Benefits of Pavement Management</td></tr>
<tr><td>Author(s)</td><td>Lynne Cowe Falls and Susan Tighe</td></tr>
<tr><td>Publisher</td><td>Public Works Management & Policy, Vol. 8 No. 3: 176-191, January 2004</td></tr>
<tr><td>Abstract</td><td>Roads and highways generally represent the single largest asset value of public infrastructure. Preservation of this asset value through timely and cost-effective maintenance and rehabilitation presents an enormous financial, management, and technical challenge to public agencies. Until recently, agencies have relied on designated or “silo” systems for pavement, bridge, and other management systems; which shared common elements of data collection, analysis, and reporting. Successful implementation of asset management requires a methodology for trade-off analysis between competing silos at the strategic level. Ultimately, many agencies may need to significantly change their business decision-making process, potentially resulting in the costs of implementation outweighing the benefits. This article describes frameworks for using longitudinal data to conduct a cost-benefit analysis of management system implementation. It also demonstrates how the same data can be used to improve technical models, thereby producing immediate benefits to the agency through enhanced decision making and, ultimately, reduced costs.</td></tr>
<tr><td>Key Words</td><td>Pavement, asset management, highways, management, benefit-cost</td></tr>
<tr><td>Research Strategy</td><td>
</td></tr>
<tr><td>Data Used</td><td>Rehabilitation funds, Pavement Quality Index (PQI), vehicle miles traveled (VMT), value of road network, PMS development costs (operation and equipment)</td></tr>
<tr><td>Model</td><td>
<table>
<tr><th>Description</th><th>Road Needs (Pre-PMS: 1981-1986)</th><th>PINS/RIPPS (Post-PMS:1986-1990)</th></tr>
<tr><td>Rehabilitation funds</td><td>$200 million (40mil*5 yrs)</td><td>$200 million (40mil*5 yrs)</td></tr>
<tr><td>PQI</td><td>6.3 (1986)</td><td>6.8 (1990)</td></tr>
<tr><td>Length</td><td>11,909km</td><td>12,767km</td></tr>
<tr><td>VKT</td><td>20,000 km</td><td>20,000 km</td></tr>
</table>
</td></tr>
</table>

Savings on vehicle operating costs	$492 million	
Replacement value	$5.38 billion	$5.80 billion
- adjusted for PQI	$3.39 billion	$3.94 billion
Increase in value (agency savings)	$550 million ($3.94 billion - $3.39 billion)	
Total savings	$1.042 billion ($492 million + $550 million)	
Costs		
PMS development	$0.65 million (1)	
Operating costs (5 yrs)		
a)$42/km (including test)	$5 million (2)	
b)$25/km (excluding test)	$2.9 million (3)	
Equipment costs	$0.3 million (4)	
Total costs		
1+2+4	$5.95 million	
1+3+4	$3.85 million	

test: biennial test for surface distress, roughness, and strength

- Savings on vehicle operating costs (user costs)

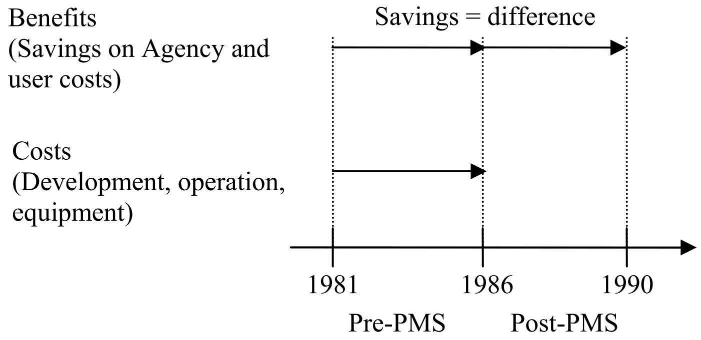
Brazil United Nations Development Plan (UNDP) study
VOCj = (a + b PQIj). (Vehicle Miles Traveled) *. IFj * DFj
Where, VOCj = the vehicle operating cost for year j
PQIj = Pavement Quality Index for year j
IFj = Inflation factor
DFj = Discount factor

- Adjusted replacement value

Assumption: Replacement value equals a PQI of 10 (i.e., all roads in the network are new).

  - 1981-1986: PQI = 6.3 and Replacement value $5.38 billion
    6.3/10*5.38 = $3.39 billion
  - 1986-1990: PQI = 6.8 and Replacement value $5.80 billion
    6.8/10*5.80 = $3.94 billion

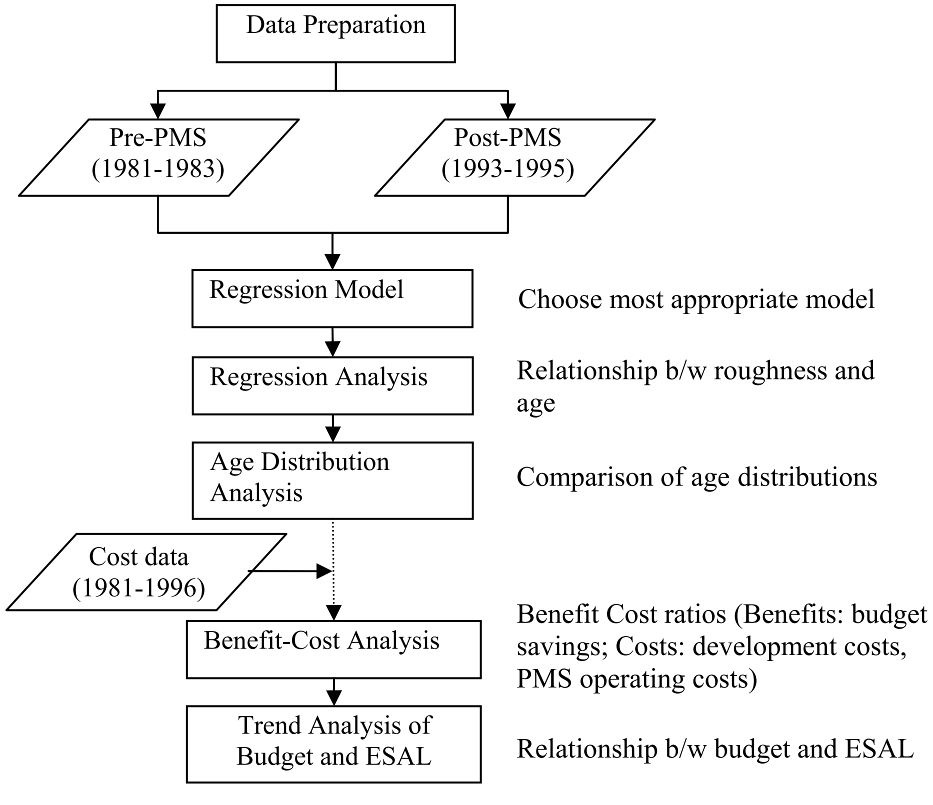
- Benefit cost analysis
  Benefits: savings on user costs, savings on agency costs between the two periods
  Costs: PMS development, operating, and equipment costs from 1981 to 1986 (implementation period)

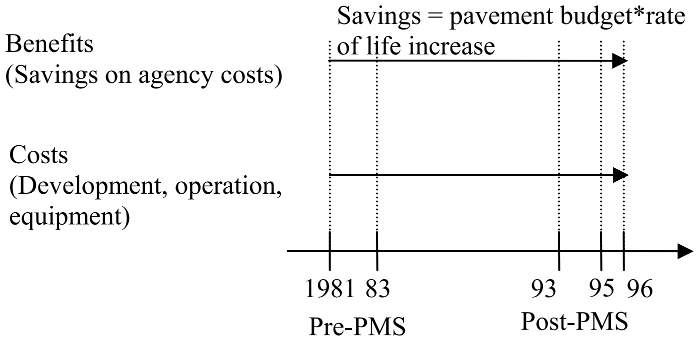
<table>
<tr><td></td><td>
</td></tr>
<tr><td><i>Result</i></td><td>
<table>
<tr><th></th><th colspan="3">Benefit</th></tr>
<tr><th>Cost</th><th>User cost savings: $492 million</th><th>Agency savings: $550 million</th><th>Total: $1.04 billion</th></tr>
<tr><td>Including test: $5.95 mil</td><td>1:82</td><td>1:92</td><td>1:175</td></tr>
<tr><td>Excluding test: $3.85 mil</td><td>1:132</td><td>1:142</td><td>1:271</td></tr>
</table>
• Large benefit-cost ratio (>82)
• Not all of the cost savings (user or agency) result solely from the PMS implementation, some savings would have occurred as a result of the expenditure of $235 million in rehabilitation and new construction.</td></tr>
<tr><td><i>Pros</i></td><td>• PQI is a good measurement to discuss the benefit of implementation of PMS because many agencies employ PQI and hold its records.</td></tr>
<tr><td><i>Cons</i></td><td>• Pre-PMS consists data between 1981 and 1986 even the PMS was implemented from 1980 to 1985. Hence, Pre-PMS data are not completely derived from the time period before PMS implementation.
• The model is not sensitive to budget constraint (rehabilitation funds), since it is based on the assumptions: the expenditures for rehabilitation of both Pre-PMS and Post-PMS are same.
• In order to adjust the replacement value, the study uses interpolation relationship between PQI and the value. Since the value is derived from repair costs, it is considered that the relationship would not be linear. This is similar to Omar’s case.
• “Replacement cost (value)” is the price, at current market value, required to return an asset new condition.
• Replacement cost = AC * Area
• Where, AC = Average cost of construction per square meter [Cowe Falls et al. 2004]
• PMS operating costs need the road length. This study uses the network length in 1986. What if the length increases during the Pre-PMS period? Strictly speaking, it is required to consider the increase.</td></tr>
<tr><td><i>Others</i></td><td>• The equation for vehicle operating cost may be developed in Brazil by</td></tr>
</table>

	UNDP. It is required to know whether the equation is applicable to other countries. • The benefits are derived from both Pre-PMS and Post-PMS periods, while the costs are derived from Pre-PMS period only. It is important to design how to extract benefits and costs in the benefit cost analysis in order to measure the benefits of PMS implementation. • They concluded that some savings would have occurred from the PMS implementation since benefit-cost ratio is lager than 82. However, it can be said that they neglect other costs or overestimate the benefits.

APPENDIX B. METHODS (continued)

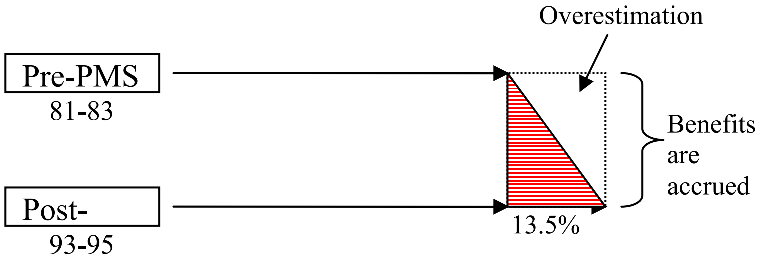
Category: pavement; Type: quantitative

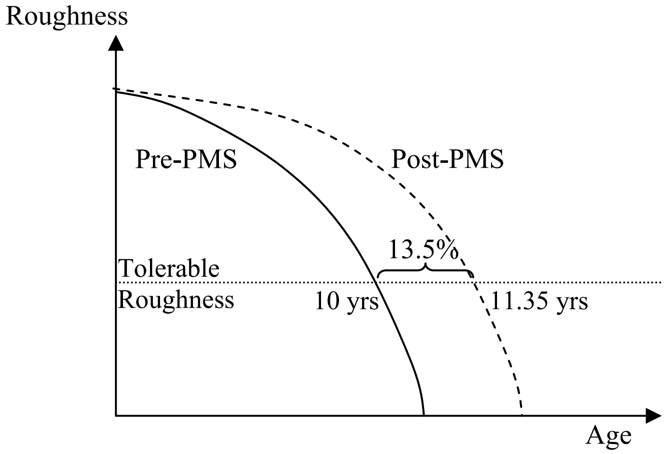
Title	Measurable Benefits Obtained from Pavement Management
Author(s)	W. Ronald Hudson, Stuart W. Hudson, Willem Visser, and Virgil Anderson
Publisher	5th International Pavement Management, Seattle, 2001
Abstract	Pavement Management began in 1966 and is now used throughout the world. Since the advent of PMS, most people have generally been aware of the benefits that pavement management yields to an agency and to the riding public. However, only recently has it been possible to actually quantify the benefits obtained. This paper describes benefits of pavement management and quantifies those benefits with data obtained from the Arizona DOT, which has used pavement management for 18 years. Benefits derived range from 8.6 to 13.5% of total pavement budgets. Benefits cost ratios ranging from 33 to 1 up to 51 to 1 for funds expended on PMS can be obtained. The paper also outlines the statistical methodology that individual agencies can also use to define benefits in their own state or agency if they have adequate data.
Key Words	Pavement Management System, Arizona DOT, before and after comparison, regression analysis, benefit-cost ratio
Research Strategy	
Data Used	PMS data for 105,000 pavement condition records, representing 16 years of data for about 7,000 miles of roadway. • Before PMS: three years (1981-83) of data or 20,091 records • After PMS: three years (1993-95) of data or 20,230 records • Although a PMS was implemented in 1980, this study used data between

	1981 and 83 because there was no data on pavement condition existed prior to 1981.
Model	• Regression model Roughness = {a + b * (age)}^2 – the roughness is by far the best measures of performance and shows best correlation with age for the data set among five measures (roughness, cracking, flushing, friction, and patching) Pre-PMS: RI = {8.09 + 0.1048 * (age)}^2, R-square = 0.07 Post-PMS: RI = {7.98 + 0.0993 * (age)}^2, R-square = 0.16 • Age distributions for the two time periods A graph showing the age distributions (horizontal axis: age (years); vertical axis: frequency) of all roads' pavement for the two time periods. • Benefit-cost ratios Benefits: savings on pavement budgets between 1981 and 1996 Costs: PMS development and operating costs between 1981 and 1996  • Budget and ESAL A graph showing the increases of budget and ESAL from 1981 to 1995.

Result	• Pavements now last 2.0 years or 13.5% longer on the average since the advent of pavement management then they did prior to the development of PMS before reaching the tolerable roughness level.
	  o 8.6% when using the 95% confident minimum interval values.
	• During the Pre-PMS Period, a large percentage of the roads were younger than 13 years in age, while the Post-PMS Period pavements were reasonably distributed over a 23-year age range.
	  o The roads are lasting longer under good pavement management practices.
	• The overall benefit/cost ratio is approximately 51 to 1.
	  o 33 to 1 when using the minimum confidence interval values.
	• More traffic is being served at a somewhat flat budget.

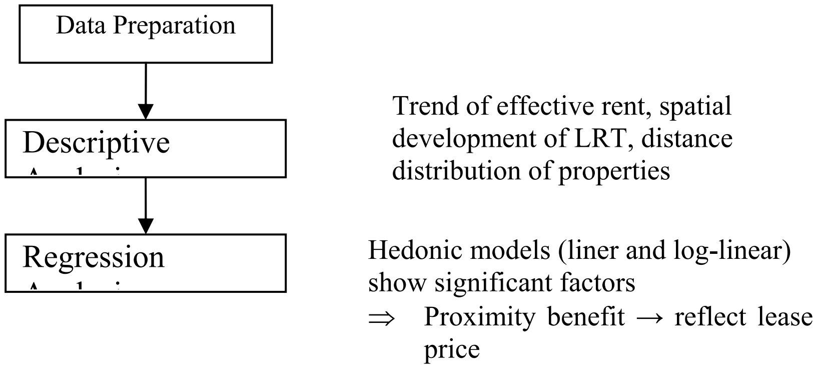
Pros	• The process is very comprehensive and applicable to other agencies. • This study addressed the trends of traffic and budget. The trends made the result of which a PMS has made pavements life longer more persuasive. Many papers don't address this point. o Traffic ↑; budget →; and life ↑, so PMS is beneficial. • This study employs sensitivity analysis using the 95% confident interval values in both the regression analysis and benefit-cost analysis.
Cons	• Pre-PMS includes data gathered in the time period between 1981 and 83, after the PMS implementation, due to data availability. Authors assumed that PMS has not yet had any effect on the performance of the pavement. If so, when would there occur effects? • Only three-year periods are used in the study to analyze the benefits of PMS over 16

	years. If the benefits are accrued as the authors mentioned, it is necessary to analyze the whole years. • Benefits, savings on pavement budget, may be overestimated based on the assumption: the average calculated benefits are 13.5% of the total pavement budgets.  • Because the benefits and the costs are aggregated over 16 years from 1981 to 1996, the benefit-cost ratio does not show the benefits of the PMS. It shows the effectiveness of Arizona DOT's business using the PMS over 16 years.

Others	• The assumption which "the average calculated benefits are 13.5% of the total pavement budgets because pavements last 13.5% longer on average" may not be reasonable. It is required to make sure the relationship between life and budget whether they are in proportional relationship.
	  o Annual expenditure for pavement maintenance and rehabilitation can be used as an alternative method.
	
	
	• It is required to decide appropriate analysis horizon. If we set longer horizon, it would be easy to obtain higher benefits of PMS implementation.
	  o E.g., we have no increase of pavement life if we set 10 year-horizon, while we have 1.35 year increase of life if we set 12 year-horizon.

APPENDIX B. METHODS (continued)

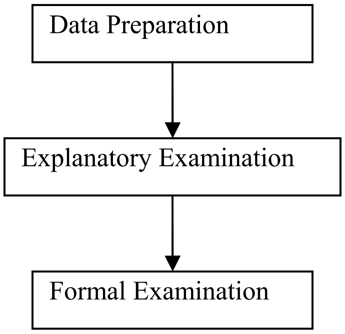
Category: transit and other; Type: quantitative and qualitative

Title	Light Rail Proximity: Benefit or Detriment in the Case of Santa Clara County, California?
Author(s)	Rachel R. Weinberger
Publisher	Transportation Research Record 1747: 104-113, 2001
Abstract	When the public sector sponsors projects to promote general welfare, disproportionate benefits or disproportionate burdens often fall on individuals. In Santa Clara County, California, private property owners sued the county for damages, claiming a burden due to the existence of light rail transit (LRT). By looking at rental rates for commercial property, the present research tests several hedonic specifications to determine what effect, if any, LRT has on proximate property values. It also compares transit accessibility with highway accessibility as determinants of rent. An understanding of this effect allows the county to make informed decisions in its defense against the suits brought and allows other government entities to make informed decisions with respect to the building of future LRT systems. The results indicate that, when controlling for other factors, properties that lie within 0.8 km (0.5 mi) of a light rail station command a higher lease rate than other properties in the county. When controlling for highway access, the rail proximity benefit was maintained, and it was shown that highway coverage in the county is so dense that there are no particular locational advantages associated with highway coverage.
Key Words	Light rail transit (LRT), proximity, hedonic
Research Strategy	
Data Used	3,701 lease transaction records collected between 1984 and 2000 and geocoded. (address, lease date, lease term, lease area, total building area, name of the tenant, name of the owner, building type, lease type, effective rent, coupon rent, terms and conditions of the rental agreement, tenant improvement allowances, existing tenant improvements per square meter, building interior designator)
Model	Regression analysis using hedonic models Price = f (constant, location controls, transaction year, improvements, lease type, lease length, distance to transit, (distance to highway))
Result	• The presence of the light rail system has conferred a rental premium on office properties that lie within its catchment or service area. • After controlling for factors such as length and type of lease, building improvements,

	regional and local economic cycles, and location, properties that lie within 0.8 km (0.5mi) of a light rail station command higher lease rates than other properties in the county. • In every model the transit proximity premium was shown to exist and decrease with distance. • When controlling for highway access, the rail proximity benefit was maintained, and it was shown that highway coverage in the county is adequately dense such that no particular locational advantages are associated with highway coverage.
Pros	• Regression analysis allows us to investigate what factors significantly influence lease price.
Cons	• The results of regression analysis don't show cause and effect relationships between dependent and independent variables. Hence, it is required to interpret the relationships based on subjective interpretation of the coefficient. For example, lease price may affect lease type, lease length, distance to transit, and so on.
Others	• The analysis is based on six assumptions. o The market is in equilibrium. o The study area represents a single market. o What factors affect price is known; data representing the factors can be obtained. o There is continuous product differentiation along the dimensions included as explanatory (independent) variables. o Consumers share common utility functions that they use to guide their decision-making processes. o There is no friction in moving; there is no arbitrage, nor are there transaction costs. • The analysis uses lease price as a measure corresponding to the benefit of LRT, that is, proximity.

APPENDIX B. METHODS (continued)

Category: ITS and transit; Type: quantitative

Title	Productivity Benefits and Cost Efficiencies from Intelligent Transportation System Applications to Public Transit: Evaluation of Advanced Vehicle Location
Author(s)	David Gillen, Elva Chang, and Doug Johnson
Publisher	Transportation Research Record 1747: 89-96, 2001
Abstract	Total factor productivity (TFP) techniques were used to develop measures of productivity performance for public transit systems of varying size and location. This baseline is used to examine the potential contribution of alternative advanced vehicle location (AVL) applications. TFP aggregates outputs on the basis of their revenue contribution and inputs on the basis of their relative importance to total costs to calculate the overall transit firm productivity as a function of these quantities. This approach provides a measure of efficiency contribution and identifies the instruments that can be used to achieve these gains. The results from the study are insightful. AVL was found to be an important factor in both system performance and cost savings. The introduction of AVL had a positive and significant impact on transit firm productivity. Improvements in productivity and better service information can be obtained through use of AVL. In the bus fleet regression, AVL has a negative coefficient, including that the use of AVL by a transit firm will result in fewer buses used given the number of vehicle miles and number of passenger trips. Similarly, cost per vehicle mile was found to be lower when the transit firm used AVL. In addition to these cost savings, research indicates that given fleet size and usage AVL will reduce the annual maintenance hours for a firm.
Key Words	Total factor productivity (TFP), advanced vehicle location (AVL), ITS, productivity benefit, cost efficiency
Research Strategy	 22 agencies, with data for each firm covering 1988-1997 Examine the “gross” TFP values to see the variability over time and across agencies in the TFP measures. Regress the gross calculated measures on a set of variables that take into account the network and environment variables (and differences) across firms. Did AVL have an impact on transit firm productivity? If productivity was affected, did the impact differ across different AVL technologies? What were the drivers that underlie any productivity improvements, if any?
Data Used	Data covering the years 1988-1997 of 22 agencies where AVL is used. Data were collected from FTA and are available for download for years after 1992 (www.fta.dot.gov).

Model	Total factor productivity (TFP) which aggregates outputs on the basis of their revenue contribution and input on the basis of their relative importance to total costs. A mutual TFP index, which allows bilateral comparisons across firms and over time: $\ln\left(\frac{TFP_k}{TFP_l}\right) = \frac{1}{2}\sum_i (R_i^k + \overline{R_i})\cdot(\ln Y_i^k - \ln\overline{Y_i}) - \frac{1}{2}\sum_i (R_i^l + \overline{R_i})\cdot(\ln Y_i^l - \ln\overline{Y_i})$ $-\frac{1}{2}\sum_i (S_n^k + \overline{S_n})\cdot(\ln X_n^k - \ln\overline{X_n}) + \frac{1}{2}\sum_i (S_n^l + \overline{S_n})\cdot(\ln X_n^l - \ln\overline{X_n})$ where Y's = outputs, such as passengers; X's = inputs, such as fuel, labor, and capital; $\overline{R}$ = revenue share of output k for firm or time period i averaged over all firms and time periods; and $\overline{S}$ = cost share of input k for firm or time period n averaged over all firms or time periods. A regression equation: $TFP_{i,t}$ = f (output, capital, time, AVL, firm dummy) where $TFP_{i,t}$ = measure of TFP of transit firm i in time period t; output = measure of firm vehicle revenue miles or passenger miles or trips; time = variable to capture any trend effects; and AVL = dummy variable, indicating that AVL was used.
Result	The overall assessment of AVL is that it provides a level of benefits for both consumers and transit agencies. Higher numbers of passenger trips were found when the transit firm used AVL. The more significant contributions were in improving productivity and cost efficiency. Whether output was measured as passenger oriented or service oriented, factor productivity was greater with the use of AVL. The sources of the productivity gains came from better use of capital, need for fewer buses, generally more efficient use of fuel and energy, and a reduction in the amount of labor needed for vehicle maintenance and operations.
Pros	The regression equation allows us to investigate what factors significantly influence productivity. The coefficient of the use of AVL shows how much contribute to productivity.
Cons	Without good data source, it is difficult to conduct the TFP. The TFP provides coefficients which are scales of relationship between independent variables (e.g., vehicle miles, buses, year, AVL, etc.) and dependent variables (e.g., passenger miles, revenue miles, etc.). The coefficients show how much the variables relate each other. However, they don't show cause and effect relationships among the variables. Hence, it is required to interpret the relationships based on subjective interpretation of the coefficients.
Others	It is important to determine what output units are appropriate to measure impacts of AVL; and identify drivers of AVL on cost efficiency and services. This study

	uses: vehicle revenue miles, passenger miles, and passenger trips for measuring impacts passenger trips, cost/vehicle mile, fleet size, and fuel use for identifying drivers

Category: ITS; Type; quantitative

Title	Cost-Benefit Analysis on Deployment of Automated Highway Systems
Author(s)	Bin Ran, Kwun Yee Kenny Lee, and Haikun Dong
Publisher	Transportation Research Record 1588: 137-144, 1997
Abstract	The optimal ranges of traffic flow and capacity will be determined for selected scenarios, in which different proportions of automated and conventional traffic will operate simultaneously in an automated highway system (AHS). It is found that there will be a substantial increase in the net benefit and the traffic flow and capacity ranges when there is a higher proportion of AHS traffic. The optimal range of capacity refers to the maximum range of traffic volumes, for which there will be some net benefit, which is the difference between the total cost and the total benefit for each flow. The total cost represents the production and operating costs of the infrastructure and the expenditure borne by the user, whereas the total benefit refers to the time saving to the user. It is concluded that more AHS vehicles should be produced in order to achieve economic efficiency, improved traffic capacity, and safety in travel.
Key Words	Cost-Benefit Analysis, automated highway systems (AHS), ITS
Research Strategy	Cost-benefit analysis to prioritize six scenarios by showing net benefit. Scenarios have different AHS corridor types and AHS vehicle percentages.
Data Used	Agency system costs: roadway infrastructure, traffic management center operation, physical infrastructure construction, AHS construction User costs: in-vehicle equipment Benefits: time saving (traffic flow, density, jam density, speed, free-flow speed, number of vehicles in a platoon, length of vehicle)
Model	Net benefit = benefits – (agency system costs + user costs) Discount rate: 6%; analysis period: 20 years
Result	The total cost decreases as a higher number of AHS and conventional vehicle operate in the system, since the operating cost can be shared by more entities. The total cost can reach the lowest in the 80 percent AHS scenario because more capacity can be handled in an hour. The benefit can reach its climax for the 80 percent AHS scenario, since this proportion of AHS traffic can generate the highest average velocity. If a higher percentage of AHS vehicles are operating in the scene, the net benefit for each benefit for each flow will be higher.
Pros	This study showed the most beneficial traffic flow by showing net benefit.
Cons	This study needs to consider changes of both discount rate and analysis period as a sensitive analysis. The need is for future analysis study only.
Others	The objective of this relative scenario evaluation (i.e., cost-benefit analysis) is to prioritize scenarios, so it is not important to consider selection of benefit/cost criteria such as time saving etc. The important is to use consistent criteria. However, it is necessary to consider what criteria are used if focus on estimating benefit. Cost calculation is not clear.

APPENDIX C. VTRANS' DATA FOR VTRANS CASE STUDY

This appendix documents the data provided by VTrans for the case study in Section 4.1. The data covers 14 years of pavement condition for all sections of the network in Vermont. The first section of the appendix lists the tables, fields and descriptions for the data from the PMS. The second section documents the variables in the worksheets generated to simulate a worst first condition.

Access database (with PMS)

Table	Fields	Description
Analysis_Sections	ElementID	
	AADT	
	ALCR	Alligator Cracking Index
	COM_COST	Committed Treatment Cost
	COM_TRT	Committed Treatment
	COM_YEAR	Committed Treatment Year
	IS_NHS	Is on the National Highway System
	IS_Primary	Is on the Vermont Primary Network
	Last_Known	Last Known Treatment
	LTCR	Longitudinal Cracking Index
	Pavement_Class	Interstate=2, State System=3 Class1=1
	Pavement_Lane	Number of lanes
	Pavement_Type	THCK= Designed Pavement Structure TONS= Thin on Strong TONW= Thin on Weak AONC= Asphalt on Concrete CONC= Portland Cement Concrete
	Program_Year	
	Project_Name	
	Project_Number	Smoothness Index
	RUFF	Rut Depth Index
	RUT	Interstate=INT State System=STE Class1=CLs
	State_Class	
	Year_of_Last_Work	
	ElementKey	
Ancillary_Treatments		No data inputted
Major_Treatments	Strategy_Key MajorTrt_FinCost_2006~2018 MajorTrt_EcoCost_2006~2018 MajorTrt_Budget_2006~2018 MajorTrt_Name_2006~2018	
Minor_Treatments		No data inputted

Access database (with PMS) (continued)

Table	Fields	Description
Segment Locations	EID	Element ID
	Road	Road name
	Town_From	Road name-Town code
	Town_Begin	Town name
	Town_Begin_MM	Town milemarker
	Town_To	Road name-Town code
	Town_End	Town name
	Town_End_MM	Town milemarker
	From	End to end milemarker
	To	End to end milemarker
	AADT	Average annual daily traffic
	Class	Interstate=INT State system=STE Class1=CL1
		Number of lanes
	Lanes	Divided highway
	Divided	Is National Highway System?
	IS_HHS	Is Vermont Primary Network?
	IS_Primary	
Strategy	Strategy_Key	
	ForeignKey	
	IsDoNothing	Do nothing treatment selected
	IsMainOnly	Maintenance only treatment selected
	IsCommitted	Is committed project?
	IsBaseCommitted	
	PVBen	Present value benefit
	PVCost	Present value cost
	BC	Benefit cost ratio
	IBC	Incremental benefit cost
	IsEfficient	Does treatment fall within efficiency frontier of IBC?
	MinCost	Changes origin of IBC graph
	IsSelected	Is a treatment selected?
	FirstMajorTrt_Year	First major treatment year
	FirstMajorTrt_Name	First major treatment name
	FirstMajorTrt_FinCost	First major treatment agency cost
	FirstMajorTrt_Budget	First major treatment agency budget
	SecondMajorTrt_Year ~ Budget	
	FirstMinorTrt_Year ~ Budget	
	SecondMinorTrt_Year ~ Budget	
Treatments	ElementID	Not a Section Element ID
	ForeignKey	Relates to Strategy Key
	Year	Analysis year treatment is applied
	Treatment	Treatment applied
	BudgetCat	Agency budget category
	FinCost	Financial cost
	EcoCost	Economic cost
	Selected	Is selected

Access database (with PMS) (continued)

Table	Fields	Description
Variable_nAAV_Yearly_Cost	Strategy_Key	
	Selected	Is treatment selected?
	After_2006 ~ 2018	Cost of treatment applied after 2006…
	Initial	Initial value of variable
Variable_nCND_ALCR	Strategy_Key	
	Selected	
	After_2006 ~ 2018	Alligator cracking index variable
	Initial	Initial value
Variable_nCND_CMP_ALL	Strategy_Key	
	Selected	
	After_2006 ~ 2018	Composite Index Variable
	Initial	Initial value
Variable_nCND_LTCR	Strategy_Key	
	Selected	
	After_2006 ~ 2018	Longitudinal cracking index value
	Initial	Initial value
Variable_nCND_RUFF	Strategy_Key	
	Selected	
	After_2006 ~ 2018	Smoothness index variable
	Initial	Initial value
Variable_nCND_RUT	Strategy_Key	
	Selected	
	After_2006 ~ 2018	Rut depth index variable
	Initial	Initial value
Variable_nDAV_PAVRMENT_TYPE	Strategy_Key	
	Selected	
	After_2006 ~ 2018	Reset field if treatment changes pavement type
		Initial value
	Initial	
Variable_nDAV_TREATMENT	Strategy_Key	
	Selected	
	After_2006 ~ 2018	Tracks last treatment to return matching performance curve
	Initial	Initial value
Variable_nPV_BENEFIT	Strategy_Key	
	Selected	
	Composite	
Variable_nPV_COST	Strategy_Key	
	Selected	
	Composite	
Variable_nTRF_AADT	Strategy_Key	
	Selected	
	After_2006 ~ 2018	Traffic Variable
	Initial	Initial Traffic AADT

APPENDIX C. VTRANS' DATA FOR VTRANS CASE STUDY (continued)

Excel spreadsheet (without PMS: worst first strategy)

- Sheet "Results"

Average condition by year 2006-2019	=(Sum CMP_Len_2006 for all segments)/Total length (for Year 2006)
Traffic weighted average condition by year 2006-2019	=(Sum VMT_CMP_Len_2006 for all segments)/Total length*AADT (for Year 2006)
Percent length by condition (i.e., very poor, poor, fair, and good) by year 2006-2019	=(Sum VeryPoor2006 for all segments)/Total length (for Very Poor in Year 2006) =(Sum Poor2006 for all segments)/Total length (for Poor in Year 2006) =(Sum Fair2006 for all segments)/Total length (for Fair in Year 2006) =(Sum Good2006 for all segments)/Total length (for Good in Year 2006) Note: Iterate the equations for Year 2007~2019
Percent travel by condition by year 2006-2019	=(Sum VeryPoor2006*AADT for all segments)/Total length*AADT (for Very Poor in Year 2006) =(Sum Poor2006*AADT for all segments)/Total length*AADT (for Poor in Year 2006) =(Sum Fair2006*AADT for all segments)/Total length*AADT (for Fair in Year 2006) =(Sum Good2006*AADT for all segments)/Total length*AADT (for Good in Year 2006) Note: Iterate the equations for Year 2007~2019

- Sheet “Calculations”

EID	Element ID
Road	Road name (table “segment locations”)
From	End to end mile marker (table “segment locations”)
To	End to end mile marker (table “segment locations’)
Length	“To” – “From”
AADT	Annual average daily traffic (table “segment locations”)
Class	Interstate=INT State system=STE Class1=CL1 (“segment locations”)
Lanes	Number of lanes (“segment locations”)
Divided	Divided highway (“segment locations”)
IS_NHS	Is NHS? (“segment locations”)
IS_Primary	Is Vermont Primary Network? (“segment locations”)
CMP_2006 ~ 2019	Composite Index Variable
No name (column Z)	
2006 ~ 2019 (column AA~AN)	
No name (column AO)	Pavement Type
No name (column AP ~ CS)	
2006 ~ 2019 (column CT ~ DG)	=IF(AVERAGE(AP2:AS2)-(1.25*STDEVP(AP2:AS2))<0,0,AVERAGE(AP2:AS2)-(1.25*STDEVP(AP2:AS2)))
CMP_Len_2006 ~ 2019	=Value in 2006*Length (for Year 2006)
Avg. Cond. 2006~2019	=(Sum CMP_Len_2006 for all segments)/Total length*AADT (for Year 2006)
Length*AADT	=length*AADT
VMT_CMP_Len_2006 ~ 2019	=CMP_Len_2006*AADT (for Year 2006)
Traffic Weighted Avg. Cond. 2006 ~ 2019	=(Sum VMT_CMP_Len_2006 for all segments)/Total length (for Year 2006)
VeryPoor2006 ~ 2019	=IF(value in 2006<40,length,0)
Percent Length by Condition Very Poor	=(Sum VeryPoor2006 for all segments)/Total length (for Year 2006)
Percent Travel by Condition Very Poor	=(Sum VeryPoor2006*AADT for all segments)/Total length*AADT (for Year 2006)
Poor_2006 ~ 2019	=IF(AND(value in 2006>=40, value in 2006<65),length,0) for Year 2006
Percent Length by Condition Poor	=(Sum Poor2006 for all segments)/Total length (for Year 2006)
Percent Travel by Condition Poor	=(Sum Poor2006*AADT for all segments)/Total length (for Year 2006)
Fair_2006 ~ 2019	=IF(AND(value in 2006>=65, value in 2006<80),length,0) for Year 2006
Percent Length by	=(Sum Fair2006 for all segments)/Total length (for Year 2006)

Condition Fair	
Percent Travel by Condition Fair	=(Sum Fair2006*AADT for all segments)/Total length (for Year 2006)
Good_2006 ~ 2019	=IF(value in 2006>=80, length, 0) for Year 2006
Percent Length by Condition Good	=(Sum Good2006 for all segments)/Total length (for Year 2006)
Percent Travel by Condition Good	=(Sum Good2006*AADT for all segments)/Total length (for Year 2006)

- Sheet “Segment_Locations_Query”

EID	Element ID
Road	Road name (“segment locations”)
From	End to end milemarker (“segment locations”)
To	End to end milemarker (“segment locations”)
Length	“To” – “From”
AADT	Average annual daily traffic (“segment locations”)
Class	Interstate=INT State system=STE Class1=CL1 (“segment locations”)
Lanes	Number of lanes (“segment locations”)
Divided	Divided highway (“segment locations”)
Is_NHS	Is NHS? (“segment locations”)
Is_Primary	Is Vermont Primary Network? (“segment locations”)
AADT_2006 ~ 2018	Traffic valuables (“Variable_nTRF_AADT”)
Initial	Initial AADT
CMP_2006 ~ 2018	Composite Index Variable (“Variable_nCND_CMP_ALL”)
VMT_2006 ~ 2018	Not used
CMP*VMT_2006 ~ 2018	Not used

APPENDIX D. VTRANS' PERCENT LENGTH BY PAVEMENT CONDITION

This appendix documents the results of the analysis of VTrans data in terms of the percent length by pavement condition depicted. Figure 89 to Figure 96 show the proportion of pavements in each category of condition by year. These figures are similar to Figure 27 to Figure 34 in Section 4.1 that depict percent travel by pavement condition for the VTrans case study.

<u>With PMS</u>

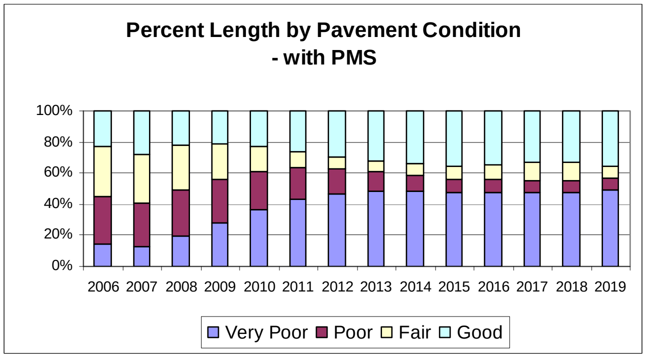


Figure 89. Percent length by condition with PMS (All)

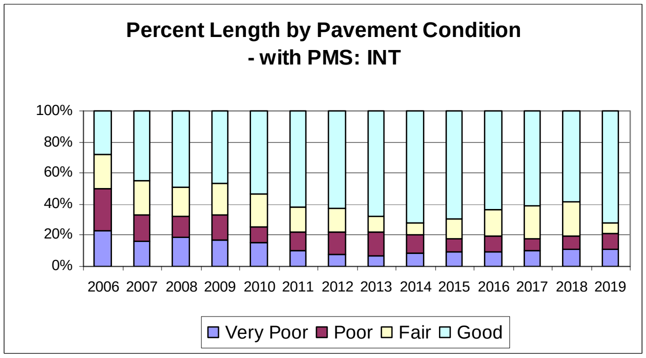


Figure 90. Percent length by condition with PMS (INT)

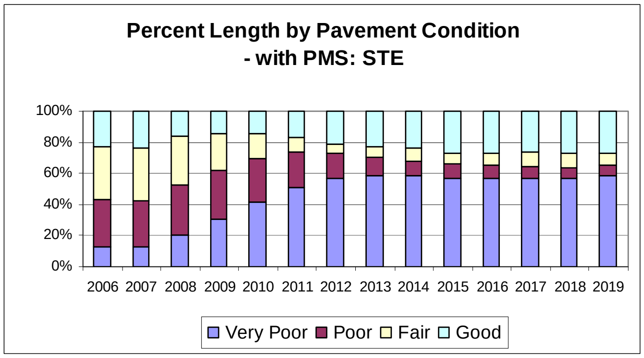


Figure 91. Percent length by condition with PMS (STE)

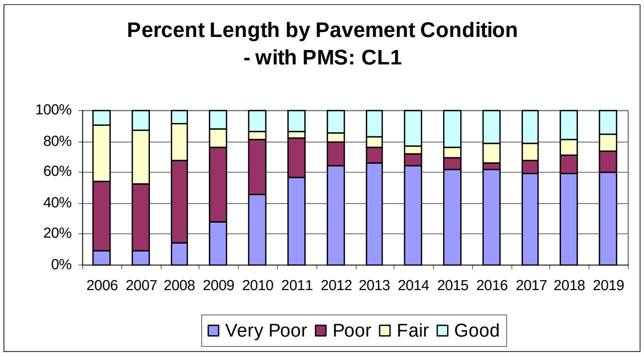
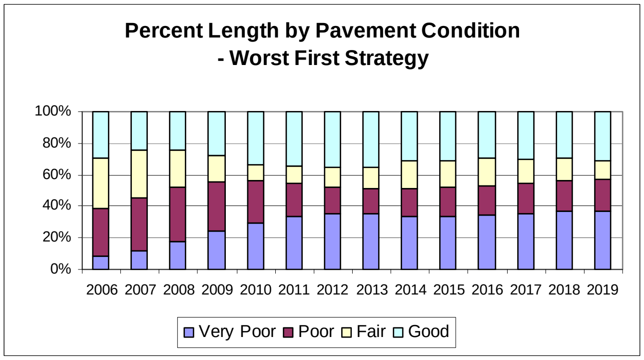


Figure 92. Percent length by condition with PMS (CL1)

<u>Without PMS (worst first strategy)</u>



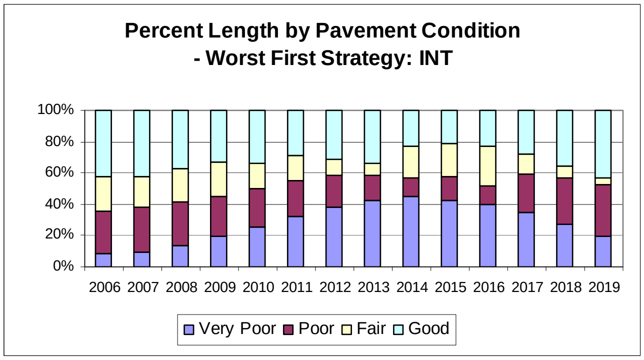


Figure 93. Percent length by condition without PMS (All)

Figure 94. Percent length by condition without PMS (INT)

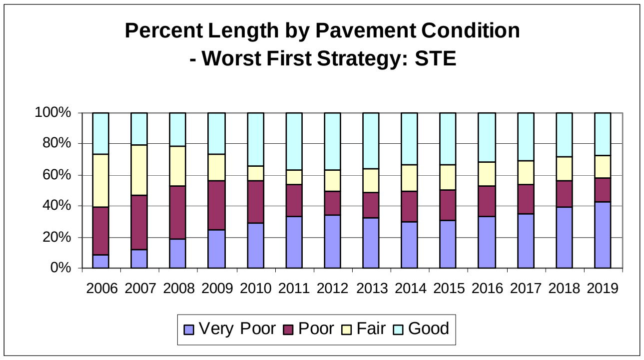


Figure 95. Percent length by condition without PMS (STE)

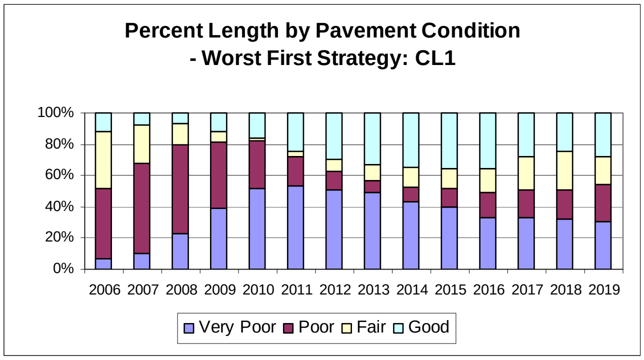


Figure 96. Percent length by condition without PMS (CL1)

APPENDIX E. HERS-ST PERFORMANCE MEASURES

This appendix presents performance measures available in HERS-ST (U.S. DOT and FHWA, 2006a). These measures are used in "descriptive analysis using with and without data" in Section 4.2.

System Conditions: Initial conditions of the highway system and its conditions after each funding period.

Field	Description
Mile	Number of miles analyzed
Lane-Miles	Number of lane-mile analyzed
Average PSR	Average PSR value of the analyzed highway sections
Average IRI	Average IRI value of analyzed highway sections
Average Speed – Peak	Average peak, off-peak and overall speed (MPH) on the highway sections
Average Speed – Off Peak	
Average Speed – Overall	
Delay – Zero Volume	Average delay (hours per 1000 VMT) for zero traffic volume, delay caused by incidents, other delays and total average delay on the highway sections
Delay – Incident	
Delay – Other	
Delay – Total	
VMT – 4 Tire Vehicle	Total vehicle miles traveled for 4-tire vehicles, single-unit and combination trucks and the overall VMT of the highway sections
VMT – Single Unit Trucks	
VMT – Combination Trucks	
VMT – All	
VHT – 4 Tire	Total vehicle hours of travel-time for 4-tire vehicles, single-unit and combination trucks and the overall VHT of the highway sections
VHT – Single Unit Trucks	
VHT – Combination Trucks	
VHT - All	
Travel Time Costs – 4 Tire Vehicles	Travel time costs (dollar per 1000VMT) for 4-tire vehicles, trucks and overall
Travel Time Costs – Trucks	
Travel Time Costs – All	
Operating Costs – 4 Tire Vehicles	Operating costs (dollar per 1000VMT) for 4-tire vehicles, trucks, and overall.
Operating Costs – Trucks	
Operating Costs – All	
Crash Costs	Costs of crashes (dollar per 1000VMT)
Total User Costs	Costs to users (dollar per 1000VMT)
Crash Rate	Rate at which crashes occur (per 100 million VMT)
Injury Rate	Rate at which injuries occur (per 100 million VMT)
Fatality Rate	Rate at which fatalities occur (per 100 million VMT)
Maintenance Costs	Average annual maintenance costs (dollar per 1000 mile)
Emissions Costs	Average pollution damage cost (dollar per 1000 VMT)
BCR of Last Improvement	BCR of the last improvement in the funding period
IRI	Percentage of mileage/VMT below the user-specified IRI deficiency thresholds
PSR	Percentage of mileage/VMT below the PSR reconstruction, deficient, and user-specified deficiency thresholds
VCR (Volume to Capacity Ratios)	Percentage of mileage/VMT below the VCR deficiency thresholds
Lane Width	Percentage of mileage/VMT below the deficient and user-specified lane width deficiency thresholds

System Conditions (continued)

Field	Description

Shoulder Width	Percentage of mileage/VMT below the deficient and user-specified shoulder width deficiency thresholds
Surface Type	Percentage of mileage/VMT below the deficient and user-specified surface type deficiency thresholds
Horizontal Alignment	Percentage of mileage/VMT below the deficient and user-specified horizontal alignment deficiency thresholds
Vertical Alignment	Percentage of mileage/VMT below the deficient and user-specified vertical alignment deficiency thresholds

APPENDIX E. HERS-ST PERFORMANCE MEASURES (continued)

Improvement Statistics: Aggregate statistical information about the costs, values and benefits of treatments on the highway system.

Field	Description
Total Initial Cost	Total initial cost of the selected treatments
Lane-Miles Improved	Total number of lane-miles added by the selected treatments
Average BCR	Average benefit cost ratio of the selected treatments
Mile Improved	Total number of highway miles improved
Lane-Miles Added	Total number of lane miles added by the selected treatments
Capital Requirements by IBCR Range (incremental range of benefit cost ratio)	Capital required to implement the selected treatments
Sample Sections by IBCR Range	Total number of sample sections affected by the selected treatments
Miles Improved by IBCR Range	Total number of highway miles improved
Travel-Time Benefits by IBCR Range	Travel-time benefits to user-benefits rations (This data express the percentage of total user benefits which is derived from the travel-time savings.)
Total Benefits	Total benefits from implanting all the selected treatments
Maintenance Cost Savings	Total maintenance cost savings as a result of the selected treatments
User Benefits	Total user benefits which include travel-time savings, operating cost savings and safety benefits
Travel-Time Savings	Total travel-time savings from the treatments
Operating Cost Savings	Total vehicle operating-cost savings from the selected treatments (On some sections, the vehicle operating costs will show a net increase due to higher operating speeds which may appear as a negative net savings.)
Safety Benefits	Total safety benefits from the treatments (The increase in traffic on improved sections may result in more safety incidents which may appear as a negative benefit.)
Crashes Avoided	Total number of crashes that were avoided from implementing all the selected treatments
Injuries Avoided	Total number of injuries that were avoided from implementing al the selected treatments
Lives Saved	Total number lives that were saved from implementing all the selected treatments
VMT of Improved Sections	Total vehicle miles travel on the improved sections (The VMT forecasts can be used in conjunction with the estimates of costs and benefits to derive estimates of costs and benefits per vehicle mile.)
Pollution Damage Savings	Total impacts of pollution damage from the selected treatments

Section Conditions: Initial conditions of each highway section and its condition at the end of each funding period. The followings are extracted data fields related to conditions among all fields. The numbers represent field numbers addressed in the list of data fields in HERS-ST user's guild (U.S. DOT and FHWA, 2006a).

No.	Field	Description
Improvement		
16	Improvement Type	Treatment type codes
17	Lanes Added	Number of lanes added by the treatment
18	Capacity Increase	Increase in peak capacity as a result of the treatment
19	Type of Selection	Roles played by HERS-ST and the User in selecting the treatment
20	Benefit Cost Ratio	Benefit Cost ratio of the most cost-effective treatment identified by HERS-ST
21	Improvement Cost	Total initial cost of the treatment
Characteristics at End of Funding Period		
22	Access Type	The values in these fields reflect the characteristics of the highway section at the end of the funding period with all recommended treatments implemented.
23	Lane Width	
24	Shoulder Type	
25	Shoulder Width	
26	Median Type	
27	Median Width	
28	Widening Feasibility	
29	Horizontal Alignment Adequacy	
30	Vertical Alignment Adequacy	
31	PSR	Estimated pavement conditions
32	IRI	
33	Average ADT	Estimated traffic volume
34	Total Lanes	Total number of through lanes, and the number of peak-period lanes in the peak and counter peak directions
35	Lanes – Peak Direction	
36	Lanes – Counter-Peak Direction	
37	Capacity – Peak Direction	Estimated peak-period capacity in the peak and counter peak directions and off-peak capacity
38	Capacity – Counter-Peak Direction	
39	Capacity – Off-Peak	
40	V/C Ratio	Peak hour-traffic/peak capacity
41	Speed – Peak Direction	Estimated speed in the peak and counter peak directions and to off-peak and average overall speed
42	Speed – Counter-Peak Direction	
43	Speed – Off-Peak	
44	Speed – Average	
45	Delay – Peak Direction	Estimated delay in the peak and counter peak directions and average overall delay
46	Delay – Counter-Peak Direction	
47	Delay – Off-Peak	
48	Delay – Average	
49	Travel Time Costs – 4-Tire Vehicles	Estimated costs in the last year of the funding period
50	Travel Time Costs – Trucks	
51	Travel Time Costs – All	
52	Operating Costs – 4-Tire Vehicles	
53	Operating Costs – Trucks	
54	Operating Costs – All	
55	Total User Costs	
56	Crash Costs	
57	Emission Costs	
58	Maintenance Costs	Estimated average maintenance costs per mile