Technical Paper

ISSN 1997-1400 Int. J. Pavement Res. Technol. 3(1):24-33
Copyright @ Chinese Society of Pavement Engineering

A Disaggregated Approach for the Computation of Network-Level Highway User Costs

Jianbin Li[1+], Yanping Sheng[1], Zongzhi Li[2], and Bei Zhou[3]

Abstract: Highway asset management is comprised of constituent management systems for physical highway assets such as pavements and bridges as well as for enhanced highway operations through improved safety, mobility, and air quality. Effective highway asset management involves the establishment of highway system goals that maximize utility to the highway agency as well as the highway user for all such management systems. As such, it is important to determine values for highway user costs and benefits for a given highway network in order to monitor the extent to which goals are being achieved and also to determine the tradeoff relationships that may exist between various aspects of highway user costs. Also, it is often desired to establish tradeoff relationships between the improvement of highway operational characteristics on one hand and physical asset conditions on the other hand. The components of highway user costs considered include those related to vehicle operation, travel time, roadway collisions, and highway vehicle emissions. The purpose of this paper is to develop statistical models for estimating network-level highway user costs using basic data on network physical and operational characteristics. The various user cost components were determined using established user cost relationships and past data on the Indiana state highway network. It was found that the average network travel speed and roadway surface condition are the significant variables that affect highway user costs. With the developed network-level user cost models, it is possible to evaluate impacts of system level decisions and ultimately to ascertain the extent to which a system level decision may influence the attainment of highway system goals.

Key words: *Disaggregated; Approach; Network-level; Highway; User costs.*

Introduction

A highway asset management can be viewed as a three-dimensional matrix structure with dimensions representing highway facilities, system goals, and operational functions [1]. A highway system includes a number of physical facilities such as pavements, bridges, drainage systems, traffic control devices, and roadside furniture. Each facility plays a unique role in the delivery of transportation services. The overall effectiveness of a highway system depends on the levels of service provided by individual facilities. System goals are specified levels of selected performance measures relating to the condition or usage of physical highway facilities. Such goals may include preservation of facility condition at or above a desired level, minimization of agency and user cost, and environmental impacts as well as maximization of safety benefits. An operational function is an activity carried out on highway facilities in order to achieve a system goal, which may include planning, design, construction, system evaluation, maintenance, and rehabilitation.

The planning, evaluation, and selection of highway investment options require an understanding of empirical relationships between highway physical and operational characteristics on one hand and service characteristics and associated user costs on the other hand. It is, therefore, important to determine values of highway user costs and benefits for a given highway network in order to monitor the extent to which goals are being achieved and also to determine the tradeoff relationships that may exist between various improvements of highway operational characteristics and different aspects of highway user costs. First, such estimated user costs enable determination of the operational costs of a highway system from the demand perspective at any given time. Secondly, such information facilitates monitoring and evaluation of the cost-effectiveness of any improvement action. Furthermore, availability of estimated user costs at network-level would facilitate comparison of the impacts of alternative actions or policies within individual component management systems, such as pavement, bridge, safety, and congestion management systems or across those management systems.

The costs associated with vehicle operation, travel time, roadway collisions, and vehicle emissions constitute overall highway user costs [2]. This paper develops statistical models for estimating network-level highway user costs using basic data on network physical and operational characteristics. The various user cost components were determined using established user cost relationships and past data on the Indiana state highway network. The proposed methodology for user cost estimation would provide policy makers and planners with a quick and easy method for estimating network-level user impacts of investments.

[1] PhD Candidate, Department of Highway Engineering, Chang'an University, Xi'an 710064, China.
[2] Assistant Professor, Department of Civil, Architectural and Environmental Engineering, Illinois Institute of Technology, IL, USA.
[3] Graduate Research Assistant, Department of Civil, Architectural and Environmental Engineering, Illinois Institute of Technology, IL, USA,
[+] Corresponding Author: E-mail ljb19690712@sina.com
Note: Submitted May 18, 2009; Revised August 21, 2009; Accepted August 24, 2009

Background Information

Review of Previous Studies

Models have been developed for estimating highway user costs at the project level, while relatively few models exist for similar estimation at the network level. Project-level user cost models typically estimate user costs as part of overall economic analysis. One of the most widely accepted is the *1977 AASHTO Manual on User Benefit Analysis and Bus-Transit Improvements* developed for the American Association of State Highway and Transportation Officials (AASHTO) and Transportation Research Board (TRB) [3]. The 1977 AASHTO manual provides cost factors, monographs, and guidelines to estimate user costs for economic analysis of most types of highway and bus transit improvements, including curve elimination, lane widening or addition, gradient reduction, new construction, intersection improvements, and bus lane decisions. Together with estimated user costs, direct costs borne by the highway agency are needed for a benefit-cost analysis and other economic assessment of alternative improvements. In 2003, the AASHTO manual was thoroughly updated by incorporating more recent findings of unit rates for individual user cost components and evaluation of Intelligent Transportation Systems (ITS) projects [4].

The Texas Transportation Institute (TTI) developed the MicroBENCOST computer program for estimating project level user costs as part of an overall highway benefit-cost analysis for projects such as individual intersection improvements, safety projects, roadway upgrade, and new road construction [5]. Vehicle emissions were also included as part of the user costs. StratBENCOST, the sister tool of MicroBENCOST, was designed to assist in comparing large numbers of project options in a jurisdiction, even at the conceptual stage. It forecasts the benefits of candidate highway investments in terms of highway user costs and environmental effects, and compares these benefits with capital and ongoing costs in terms of their net present value [6]. Key features of StratBENCOST traffic demand estimation, travel time and vehicle operating estimation, safety and collision cost estimation, environmental effects, construction and disruption cost estimation, risk analysis element to account for uncertainty, and economic evaluation criteria.

The Highway Development and Management (HDM) System (HDM-4) is a decision support software system produced by the International Study of Highway Development and Management (ISOHDM) Tools, sponsored by the World Bank, the Asian Development Bank, the U.K. Department for International Development, the Swedish National Road Administration, and other organizations. HDM-4 is used to assist road managers to predict future economic, technical, social, and environmental outcomes of possible investment decisions concerning highway assets [7]. The system is capable of conducting strategic planning studies through programmed allocation of funds to maintenance or improvement works on a network, and assesses economic and environmental impacts of alternative options at the project level. The strategic planning application involves an analysis of alternative investments over a medium- or long-term and for a selected network, giving due consideration to indirect costs associated with pavement performance and road user effects.

In response to a 1965 congressional mandate for reporting future highway investment requirements, the Federal Highway Administration (FHWA) in the early 1980s initiated the development of a model to estimate highway investment requirements using engineering standards. That model subsequently evolved into the Highway Economic Requirements System (HERS) to include an economic analysis (in the mid 1990s) and the environmental cost of vehicle emissions (in 1999). The HERS model compares the relative benefits and costs of alternative improvement options on the basis of historical information [8]. Costs include capital expenditures required for improvements, and benefits are computed as reductions in user costs such as vehicle operating costs, travel time, and roadway collisions over the life of the improved facility.

With the assumption that the marginal cost of highway travel is higher than the average cost, reflecting the fact that each additional vehicle on a highway imposes a measurable user cost on all other users at that time, Ozbay, Bartin, and Berechman [9] described a methodology for estimating full marginal transportation costs of highway transportation in New Jersey. The researchers defined the full marginal cost for each origin-destination (O-D) pair over a given time period as a function of the average cost of a trip and the congestion-related cost imposed by an additional trip to other road users. Highway transportation costs were classified as user cost, infrastructure cost, and environmental cost; cost functions were developed for each cost category, and the marginal cost functions were determined simply by taking the first order derivative of the respective cost functions.

Critiques

Most existing models for computing user costs are for the project level and require extensive amounts of data on each project for the computation. For estimating user costs at the network level at a given point in time or in response to a system improvement (or degradation), such models would need to be applied separately for each highway segment and then added to yield the overall network-level impacts. If the network is large and if all data items are not available, this can be a difficult task to accomplish. Further, the MicroBENCOST software conducts user cost estimation for a proposed project segment-by-segment and then sums up to establish the total user costs. It, however, does not consider induced demand that is captured by the concept of consumer plus as in [4, 10, 11]. The StratBENCOST software conducts risk-based analysis by considering probability distributions of input factors such as project costs, traffic volumes, and discount rates for the computation. To maintain the accuracy of the analysis, a large amount of historical data is needed to derive the probability distributions and this makes it hard for real world applications. Similarly, the HDM-4 also requires a large amount of input data, and it is primarily designed for the use at project level. A major strength of the HERS model is its application at the network level, where it can be used for benefit-cost analyses of investments. However, it is unable to completely address concurrent changes occurring in the network as this model analyzes systemwide improvement alternatives one at a time. Also, the lifetime benefits associated with an improvement are computed only for the first 5-year period, and an estimate of improvement cost is used as a proxy for its remaining future benefits, an approach that is replete with assumptions that may be unduly restrictive. To facilitate estimation of user costs at the network level, it is therefore useful to develop an approach that obviates the need to carry out separate user cost estimation for individual highway segments of the network and that utilizes only very basic and readily available data items. The present study addresses this issue and utilizes a disaggregate approach to estimate network-level user cost impacts on the basis of average traveling speed and roadway condition and annual vehicle miles of travel (VMT) by vehicle class and by highway functional classification.

Proposed Methodology

The methodological framework for network-level user cost computation is illustrated in Fig. 1. First, individual highway user cost components were identified and brief descriptions to those components were provided. Then, data collection and processing were conducted. Subsequently, the quantities of individual highway user cost components for a selected network (namely, the Indiana State Highway System) were then computed using established formula [4, 5, 12] on the basis of annual total VMT associated with the highway network. The quantities for individual highway user cost components were then converted into dollar values and were summed up to obtain the overall network-level highway user costs for each year. Later, the quantities of individual highway user cost components as well as the overall network-level highway user costs were divided by annual total VMT to establish per VMT values for individual user costs components and also the total highway user costs. Finally, those normalized values were expressed as a function of a set of basic network physical and operational characteristics.

Identification of Highway User Cost Components

The current study considers costs from vehicle operation, travel time, roadway collision, and vehicle emissions as the four major components that constitute overall highway user costs. Motor vehicle operating costs (VOC) are primarily mileage-dependent costs of running highway vehicles, including expenses for fuel, tires, engine oil, maintenance, and the part of vehicle depreciation that is attributable to highway mileage traveled. Travel time is measured in terms of vehicle-hours spent on a trip. Total travel time also includes vehicle delays that are extra travel time beyond that experienced under normal traffic conditions. Five types of delays including delay due to congestion, intersections or interchanges, railroad grade crossings, incidents, and work zones are considered in the current study. Roadway collision statistics are generally reported in three categories of decreasing severity: fatalities, injuries, or property

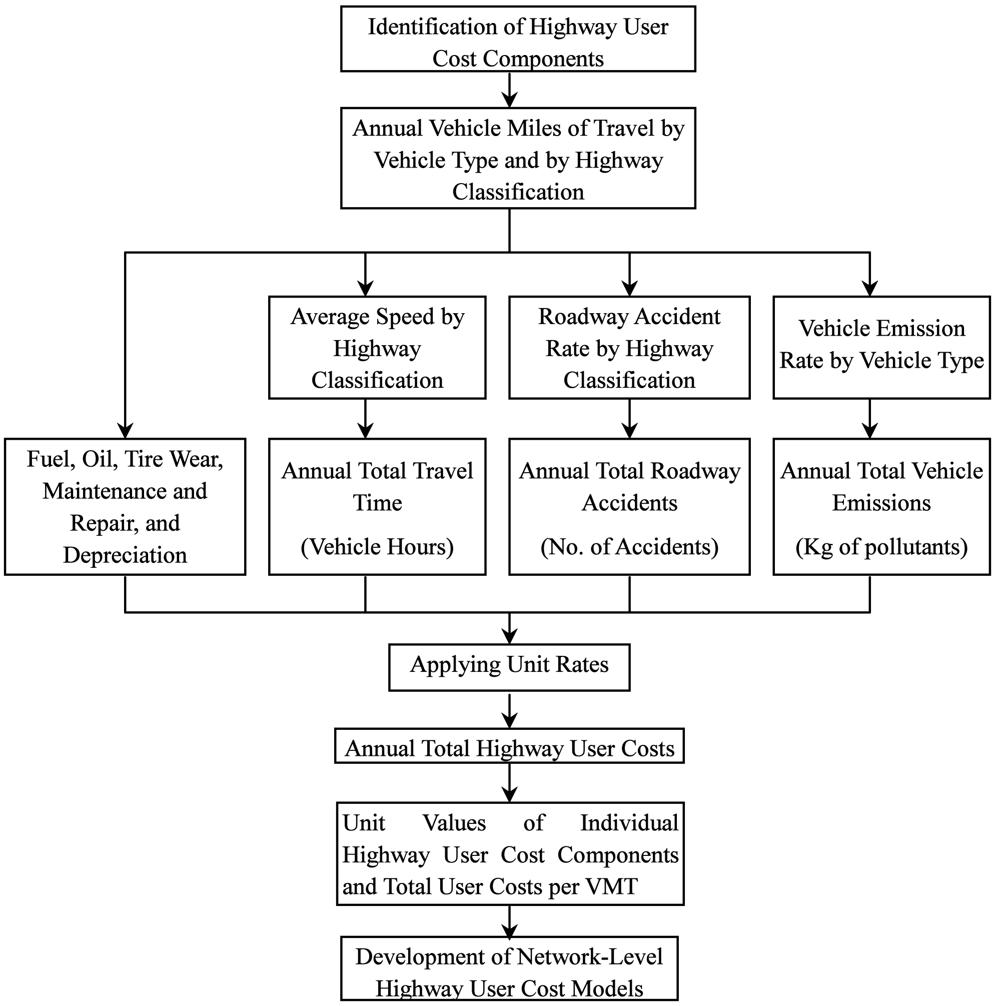


Fig. 1. Framework for Network-Level Highway User Cost Computation.

damages only (PDO). The major pollutants emitted by vehicles are carbon dioxide (CO_2), non-methane hydrocarbons (NMHC), carbon monoxide (CO), nitrogen oxides (NO_X), total suspended particles (TSP), and sulfur dioxide (SO_2).

Data Collection and Processing

As shown in Table 1, extensive data collection form period 1990-2006 were made to collect data on physical highway system inventory, operational characteristics, and price indices documented in Indiana annual Highway Performance Monitoring System reports, vehicle registration reports, construction records, traffic safety statistics, Bureau of Labor Statistics' historical price index reports, etc. The individual sets of data were integrated into a database to facilitate the computation of annual highway user costs associated with state-maintained highways in Indiana and calibration of statistical models for user cost prediction.

Computation of Individual Highway User Cost Components

The computation of individual highway user cost components was conducted using Eqs. (1-8). For VOC component, the quantities of items associated with fuel, oil, tire wear, depreciation, maintenance and repair, and vehicle idling were first computed based on annual VMT traveled by various vehicle types on different highway functional classifications. The respective quantities for individual cost items were summed up for all vehicle types and all highway functional classifications and were further adjusted after considering the effects of grade, curvature, speed change, and pavement condition of the highway network. The unit rates were then applied for the corresponding cost items to establish network-level annual total vehicle operating costs. The vehicle types and highway classifications used for the computation are listed in Tables 2 and 3, respectively.

The annual network travel time under normal traffic operations condition was computed on the basis of annual VMT and average traveling speed by vehicle type and by highway classification. The excessive travel time corresponding to delays was treated differently for delays due to congestion, intersections or interchanges, railroad crossings, incidents, and work zones. For delay due to congestion, a statewide, county-by-county, congestion analysis was performed in Indiana to identify congestion over a 20-year time span from 1995 to 2015 [14]. The benchmark volume-to-capacity ratios used were 0.9 for urban interstate; 0.8 for urban freeways, arterial, and collectors; and 0.7 for rural highway classes, respectively. Intersection delay was calculated separately for intersections with stop signs (2-way or 4-way stops) and signalized intersections. Interchange delay was computed mainly for diamond, 3-level-diamond, cloverleaf interchanges. Railroad delay was quantified based on the number of railroad crossings, the number of affected vehicles at each railroad crossing, and duration of stoppage

Table 1. Data Items Used for Highway User Cost Computation.

Data Item	Source
Daily VMT	Indiana Annual HPMS Report
Road Mileage	Indiana Annual HPMS Report
Annual Average Daily Traffic	Indiana Annual HPMS Report
No. of Lanes	Indiana Annual HPMS Report
Average Traveling Speed	Indiana Annual HPMS Report
Directional Distribution Factor	Indiana Annual HPMS Report
Peak Capacity	Indiana Annual HPMS Report
Volume/Service Flow Ratio	Indiana Annual HPMS Report
Signalization Distribution	Indiana Annual HPMS Report
Green Time Distribution	Indiana Annual HPMS Report
No. of Grade Separations	Indiana Annual HPMS Report
No. Interchanges	Indiana Annual HPMS Report
No. of Intersections	Indiana Annual HPMS Report
No. of Stop Signs	Indiana Annual HPMS Report
No. of Railroad Crossings	Indiana Annual HPMS Report
Horizontal Alignment Distribution	Indiana Annual HPMS Report
Vertical Alignment Distribution	Indiana Annual HPMS Report
Length of Curves	Indiana Annual HPMS Report
Length of Grades	Indiana Annual HPMS Report
Vehicle Registration	Bureau of Motor Vehicles Vehicle Registration Reports
Daily Miles of Travel	Bureau of Census Truck Inventory and Use Survey
IRI/PSI	Indiana Annual HPMS Report, Highway Statistics
Congested VMT	Indiana State Highway Congestion Estimates
No. of Work Zones	Indiana State Highway Construction Records
Roadway Collisions	NHTSA Annual Traffic Safety Facts
Vehicle Emissions	FHWA The Costs of Air Pollution Abatement
Price Index	Bureau of Labor Statistics Historic Producer and Wholesale Price Indices

Table 2. Vehicle Classes Used for Highway User Cost Computation [13].

Vehicle Class	Description	
1	Motorcycles	(axles: 1ST+1S)
2	Passenger Cars	(axles: 1ST+1S)
3	Two-axle, 4-tire single units	(axles: 1ST+1S)
4	Buses	(axles: 1ST+1S)
5	Two-axle, 6-tire single units	(axles: 1ST+1S)
6	Three-axle single units	(axles: 1ST+1T)
7	Four or more axle single units	(axles: 1ST+1TR)
8	Four or less axle single trailers	(axles: 1ST+2S/3S)
9	Five-axle single trailers	(axles: 1ST+2T)
10	Six or more axle single trailers	(axles: 1ST+1T+1TR)
11	Five or less axle multiple trailers	(axles: 1ST+3S/4S)
12	Six-axle multiple trailers	(axles: 1ST+3S+1T)
13	Seven or more axle multiple trailers	(axles: 1ST+2S+2T)

Note: ST-steering axle; S-single axle; T-tandem axle; and TR-tridem axle.

Table 3. Highway Classifications Used for Highway User Cost Computation [13].

Highway Classification	Description
1	Rural Interstate
2	Rural Principal Arterial
6	Rural Minor Arterial
7	Rural Major Collector
8	Rural Minor Collector
11	Urban Interstate
12	Urban Freeway and Expressway
14	Urban Principal Arterial
16	Urban Minor Arterial
17	Urban Collector

time per vehicle at each railroad crossing. The FHWA's Traffic Control Systems Handbook estimates that eight incidents per million VMT are experienced when one or more travel lanes are blocked [15]. This rate was used in the present study. The details of work zone characteristics, such as their frequency, length, duration, and geographical distribution over the highway network, were obtained from relevant sources at Indiana Department of Transportation (INDOT). The information was then processed together with the typical number of vehicles affected and the average travel speed to obtain the total work zone delay.

Roadway collisions were established using fatality, injury, and PDO rates (per million VMT) for different highway functional classifications and annual VMT by highway classification. The network-level total collisions were then established by summing up all collisions across different highway functional classifications.

The emission rates per vehicle-mile of travel by vehicle type for pollutants like CO_2, NMHC, CO, NO_X, TSP, and SO_2 from the FHWA's Costs of Air Pollution Abatement Study [16] were used to determine the network-level annual vehicle emission quantities. For each pollutant, vehicle emissions by different vehicle types were first quantified according to annual VMT by vehicle type and the total emissions were then established based on annual total VMT for all vehicle types.

The same procedure was repeated for the computation of annual VOC, travel time, roadway collisions, and vehicle emissions for each year. To obtain the annual highway user cost associated with the entire highway network, annual travel time, number of roadway collisions, and vehicle emission quantities were converted into dollar values according to their respective unit costs. These costs were then summed up with VOC to obtain annual total user costs. The unit costs adopted for the computation were updated each year, based on Producer Price Index (PPI) and Wholesale Price Index (WPI) in Indiana for various passenger cars and trucks.

$$\text{VOC} = \sum_{i=1}^{13}\sum_{j=1}^{10}\left[\left(\sum_{k=1}^{5} \text{UVOC}_{ijk}\right)\cdot \text{VMT}_{ij}\right] \tag{1}$$

$$\text{Travel Time} = \sum_{i=1}^{13}\left[\left(\sum_{j=1}^{10}\left(\frac{\text{VMT}_{ij}}{\text{Speed}_{ij}}\right)\right)\right] \tag{2}$$

$$\text{Delay}_{\text{intersections}} = \sum_{i=1}^{13}\left[\left(\sum_{j=1}^{10}\sum_{l=1}^{L}\left(N_{jl}\cdot \text{Average Delay}_{jl}\right)\right)\right] \tag{3}$$

$$\text{Delay}_{\text{railroadcrossings}} = \sum_{i=1}^{13}\left[K_m\cdot\left(\sum_{m=1}^{M}\text{TSD}_m\right)\right] \tag{4}$$

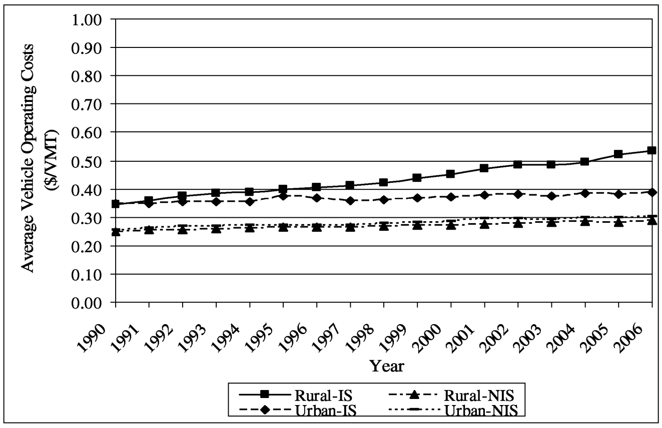
$$\text{Delay}_{\text{Incidents}} = \sum_{i=1}^{13}\sum_{j=1}^{10}\left[\text{Incident Delay}_{ij}\cdot \text{Incident Rate}_{ij}\cdot\left(\frac{\text{VMT}_{ij}}{1{,}000{,}000}\right)\right] \tag{5}$$

$$\text{Delay}_{\text{Work Zones}} = \sum_{i=1}^{13}\sum_{n=1}^{N}\left[\text{AffectedVehicles}_{in}\cdot\text{WZDuration}_n\cdot \text{WZLength}_n\cdot\left(\frac{1}{\text{Speed}_{in(1)}}-\frac{1}{\text{Speed}_{in(2)}}\right)\right] \tag{6}$$

$$\text{Roadway Collisions} = \sum_{j=1}^{10}\left[\left(\sum_{p=1}^{3}\text{CollisionRate}_{jp}\right)\cdot\left(\sum_{i=1}^{10}\frac{\text{VMT}_{ij}}{1{,}000{,}000}\right)\right] \tag{7}$$

$$\text{Vehicle Emissions} = \sum_{i=1}^{13}\sum_{j=1}^{10}\left[\left(\sum_{q=1}^{6}\text{Emission Rate}_{iq}\right)\cdot\text{VMT}_{ij}\right] \tag{8}$$

where,



Note: 1. IS- Interstate highways; NIS- Non-Interstate highways.
2. The costs are in 1990 constant dollars.

Fig. 2. Average VOC per VMT for Indiana State Highway Network by Highway Functional Classification.

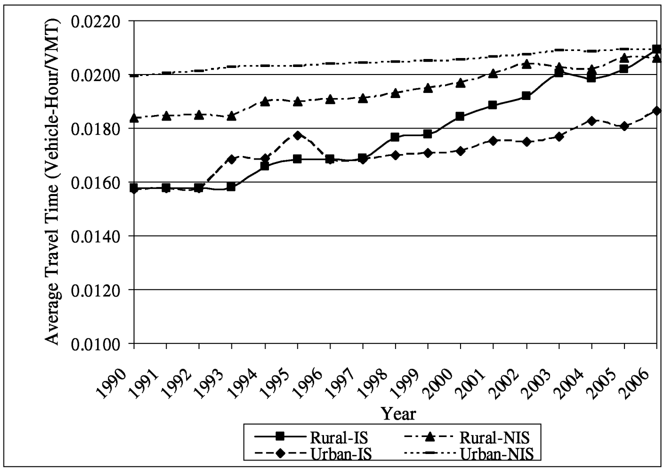


Fig. 3. Average Travel Time per VMT for Indiana State Highway Network by Highway Functional Classification.

VOC = Annual vehicle operating costs, in dollars/year;
Travel Time = Annual total travel time, in hours/year;
$Delay_{intersections}$ = Annual vehicle delay at intersections and interchanges, in hours/year;
$Delay_{railroad\ crossings}$ = Annual vehicle delay at railroad crossings, in hours/year;
$Delay_{incidents}$ = Annual vehicle delay due to incidents, in hours/year;
$Delay_{workzones}$ = Annual vehicle delay at work zones, in hours/year;
Roadway Collisions = Annual number of roadway collisions, in number of collisions/year;
Vehicle Emissions = Annual vehicle emission quantities, kg/year;
VMT_{ij} = Annual vehicle miles of travel for vehicle class *i* on highway class *j*;
$UVOC_{ijk}$= Unit cost of VOC component *k* for vehicle class *i* on highway class *j*, in $/VMT;
$Speed_{ij}$= Annual average travel speed for vehicle class *i* on highway class *j*;
N_{jl} = Number of intersections of type *l* on highway class *j*;
Average $Delay_{jl}$ = Average delay at intersection of type *l* on highway class *j*, in hours/vehicle;
K_m = Number of trains passing railroad crossing *m* per year;
TSD_m = Total stopped delay time per train at railroad crossing *m*, in hours/train;
Incident $Delay_{ij}$ = Delay time per incident by vehicle class *i* on highway class *j*, in hours/vehicle;
Incident $Rate_{ij}$ = Number of incidents per million VMT by vehicle class *i* on highway class *j*;
Affected $Vehicles_{in}$ = Number of affected vehicles of vehicle class *i* at work zone *n*;
WZ $Duration_n$= Duration of work zone *n*, in days/year;
WZ $Length_n$= Length of work zone *n*, in miles;
$Speed_{in(1)}$= Speed of vehicle class *i* approaching work zone *n*, in mph;
$Speed_{in(2)}$= Speed of vehicle class *i* in work zone *n*, in mph;
Collision $Rate_{jp}$ = Number of roadway collisions of type *p* per million VMT on highway class *j*, in number of collisions/MVMT;
Emission $Rate_{iq}$= Quantities of pollutant type *q* emitted by vehicle class *i*, in tons/VMT;
i = Vehicle class 1 to 13;
j = Highway class 1 to 10;
k = VOC component 1 to 5 for fuel consumption, oil consumption, tire wear, vehicle depreciation, and maintenance and repair;
l = Intersection type 1 to L;
m = Railroad crossing 1 to M;
n = Work zone 1 to N;
p = Collision type 1 to 3 for fatality, injury, and property damage; and
q = Pollutant type 1 to 6 for CO_2, NMHC, CO, NO_X, TSP, and SO_2.

Development of Network-Level Highway User Cost Models

Step 1 Establishing Vehicle Operating Costs, Travel Time, Roadway Collision Rate, Vehicle emission Rate, and Highway User Costs per VMT for Each Year.

The annual total VOC, travel time, roadway collisions, and vehicle emission quantities associated with the entire highway network were divided by the annual total VMT to establish vehicle operating costs, travel time, collision rate, and vehicle emission rate per vehicle-mile of travel. This computation was conducted for the entire state highway network and for smaller networks consisting of rural and urban interstate and non-interstate highways in Indiana.

Step 2 Developing Statistical Models for Unit VOC, Travel Time, Roadway Collision Rate, Vehicle Emission Rate, and Highway User Costs, Respectively.

The unit values of individual highway user cost components (such as VOC per VMT, travel time per VMT, roadway collision rate per million VMT, and vehicle emission rate per VMT) obtained for each year of the analysis period were then used as dependent variables, respectively, to establish functional relationships with roadway condition, average traveling speed, and other factors. These are listed as follows:

VOC/VMT = *f* (system condition, speed, traffic, and roadway characteristics)
Travel Time/VMT = *f* (speed, traffic, and roadway characteristics)

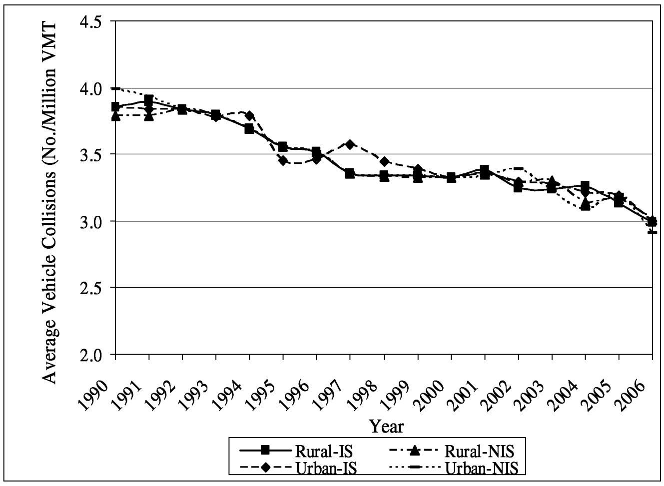


Fig. 4. Average Vehicle Collision Rate per Million VMT for Indiana State Highway Network by Highway Functional Classification.

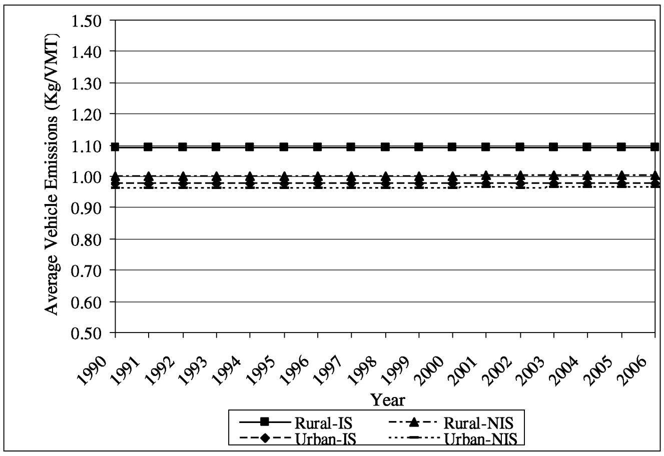


Fig. 5. Average Vehicle Emissions per VMT for Indiana State Highway Network by Highway Functional Classification.

Collision Rate/MVMT = f (system condition, speed, traffic, and roadway characteristics)

Emission Rate/VMT = f (system condition, speed, traffic, and roadway characteristics)

The statistical models were developed for the entire state highway network, rural and urban interstates, and non-interstate highways in Indiana, respectively.

Application of the Proposed Methodology

User Cost Computation

The procedure discussed in previous section was applied to compute the annual total VOC, total travel time including vehicle delays, number of roadway collisions, and vehicle emission quantities. The respective values were then divided by the annual total VMT to arrive at VOC, travel time, roadway collision rate, and vehicle emission rate per vehicle-mile of travel. (Note: the unit for roadway collision rate is the number of collisions per million vehicle-miles of travel.) The results are shown in Figs. 2 to 5.

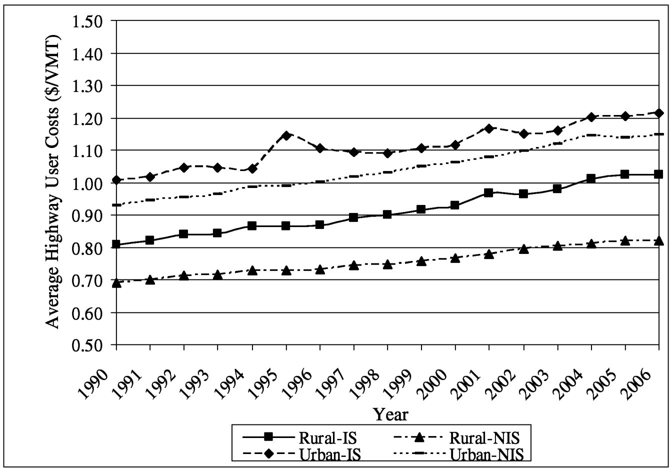


Fig. 6. Trends in Highway User Costs per VMT by Highway Functional Classification.

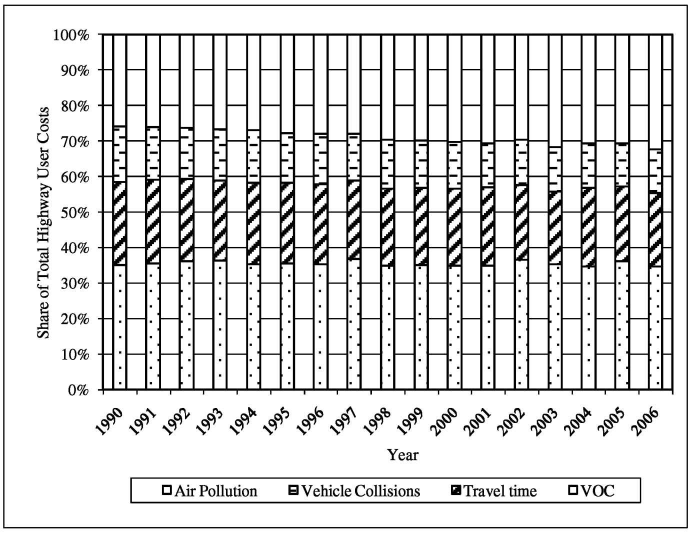


Fig. 7. Share of Total Highway User Costs by Cost Component for Indiana State Highway Network.

The travel time, roadway collisions, and vehicle emissions for one-mile of travel were then expressed in monetary terms. By applying unit costs of individual user cost components, various highway user costs per vehicle-mile of travel on Indiana state highways were obtained. The respective user costs for rural and urban interstate as well as non-interstate highways in Indiana are presented in Fig. 6. The relative shares of various user cost components are given in Fig. 7. All dollar values provided are in 1990 constant dollars. The unit costs of travel time were obtained from earlier research [5] and updated to reflect current conditions in Indiana. A similar approach was used to obtain unit cost of roadway collisions [4, 5] and vehicle emissions [16].

Highway User Cost Model Development

Model Specification

Pavement condition, speed, and vehicle miles of travel are three parameters that are routinely monitored for a highway network. Models are developed relating VOC, travel time, roadway collisions, and vehicle emissions with these commonly recorded parameters. After investigating various linear transformations and non-linear models, it was found that the best model is of the linear form shown below:

$$Y = \alpha_0+\alpha_1X_1+\alpha_2X_2+\ldots+\varepsilon \quad (9)$$

where,

Y = Dependent variable, such as VOC, travel time, roadway collision rate, vehicle emission rate, and total user costs per VMT, respectively;

X_i = A set of parameters representing system condition, average travel speed, physical highway facilities and highway geometric characteristics;

α_0= Constant term;

α_i = Model coefficients;

ε = Error terms; and

$i = 1, 2,\ldots, n$, where n is the total number of independent variables considered.

Model Calibration

Maximum likelihood estimation techniques were utilized for model estimation, and LIMDEP software [16] was used for calibration. The following equations were selected based on statistical parameters for individual user cost components and the total user costs:

$$\text{VOC: VOC/VMT} = \alpha_0+\alpha_1\text{CONDITION}+\alpha_2\text{SPEED} \quad (10)$$

$$\text{Travel Time: Travel Time/VMT} = \alpha_0+\alpha_2\text{SPEED} \quad (11)$$

$$\text{Roadway Collisions: Roadway Collisions/MVMT}=\alpha_0+\alpha_2\text{SPEED} \quad (12)$$

$$\text{Vehicle Emissions: Vehicle Emissions/VMT}= \alpha_0+\alpha_2\text{SPEED} \quad (13)$$

$$\text{Total User Costs: User Costs/VMT} =\alpha_0+\alpha_1\text{CONDITION}+\alpha_2\text{SPEED} \quad (14)$$

where,

CONDITION = Road surface condition measured in International Roughness Index (IRI), in *(in/mi)*

SPEED = Average traveling speed, in *mph*; and

α_0, α_1 and α_2 were calibrated coefficients of significant independent variables.

Model Validation

Besides selecting an appropriate model form for model calibration, the statistical significance of the estimated regression coefficient for each independent variable was investigated. That is, the null hypothesis that the coefficient is zero should be rejected if the variable is statistically significant. In addition, the sign and magnitude of each estimated coefficient should be practical and justifiable from an engineering viewpoint. For the present study, the LIMDEP software yielded estimates of the coefficients and standard error for each coefficient from which the *t*-statistics were computed. The *t*-statistic of each estimated coefficient is the estimated coefficient divided by the estimated standard error. If the *t*-statistic is large, then there is adequate evidence that the corresponding variable is significant, namely, the difference between the coefficients estimates and zero arises not from chance but from a systematic effect.

The model should also have a reasonable predictive and explanatory ability as indicated by the adjusted R^2 values representing the goodness-of-fit. In addition, Durbin-Watson statistic and LaGrange Multiplier statistic values were computed to test for autocorrelation and heteroskedasticity of error terms of individual models, respectively. For a model to be effective in prediction, the adjusted R^2 should be relatively high, the Durbin-Watson statistic should not significantly deviate from 2.0, and the LaGrange Multiplier statistic should be very low. Table 4 presents the calibrated coefficients, descriptions of significant independent variables, and model validation results.

Discussions

User Cost Levels

The present study found that VOC, travel time, and total highway user costs per vehicle-mile of travel on Indiana state highways increased slightly from 1990 to 2006. For all classes of highways on the state highway network, the values were \$0.29, 0.018 hour (or 1.1 minutes), and \$0.82 per VMT, respectively, in 1990 and \$0.36, 0.019 hour (or 1.15 minutes) and were \$1.01 per VMT, respectively, in 2006 (in 1990 constant dollars). Furthermore, the vehicle emission rate per vehicle-mile of travel, which is approximately 1 kilogram per VMT, has been quite stable over the years. This was found to be generally true regardless of highway functional classifications.

Table 4-a. Coefficients and Descriptions of Significant Independent Variables for Calibrated Models.

Vehicle Emission Rate per VMT (*kg*/VMT)							
Significant Independent Variable	Calibrated Coefficient	Rural Interstate	Rural Non-Interstate	Urban Interstate	Urban Non-Interstate	Entire Highway Network	Description of Variable
Constant	α_0	1.0925 *(80.11)*	0.9959 *(31.93)*	0.9769 *(82.21)*	0.9490 *(748.84)*	1.0014 *(245.89)*	Constant term
CONDITION	α_1	-0.000003 *(-1.43)*	-	0.000001 *(4.12)*	-	-0.00002 *(-3.78)*	Condition in IRI, *(in/mi)*
SPEED	α_2	0.00001 *(7.51)*	0.00009 *(1.56)*	0.000007 *(6.19)*	0.0002 *(10.16)*	0.00017 *(2.45)*	Average speed, *mph*
Adjusted R^2		0.95	0.82	0.73	0.88	0.90	
Durbin-Watson Statistic		2.18	1.63	1.91	1.97	1.67	
LaGrange Multiplier Statistic		0.03	0.06	0.05	0.02	0.15	

Table 4-b. Coefficients and Descriptions of Significant Independent Variables for Calibrated Models.

Highway User Costs per VMT ($/VMT)							
Significant Independent Variable	Calibrated Coefficient	Rural Interstate	Rural Non-Interstate	Urban Interstate	Urban Non-Interstate	Entire Highway Network	Description of Variable
Constant	α_0	1.8076 *(9.59)*	0.9756 *(5.24)*	2.2741 *(3.86)*	2.3701 *(36.27)*	1.3060 *(6.09)*	Constant term
CONDITION	α_1	0.0009 *(3.20)*	0.0010 *(6.49)*	0.0019 *(1.43)*	-	0.0012 *(5.65)*	Condition in IRI, *in/mi*
SPEED	α_2	-0.0170 *(-5.57)*	-0.0068 *(-2.11)*	-0.0229 *(-2.70)*	-0.0249 *(-20.38)*	-0.0106 *(-3.00)*	Average speed, *mph*
Adjusted R^2		0.96	0.97	0.77	0.96	0.98	
Durbin-Watson Statistic		1.75	1.58	1.51	2.04	2.12	
LaGrange Multiplier Statistic		0.12	0.10	0.008	0.13	0.08	

Note: 1. "-" means not significant.
2. The t-statistic values are provided in the parentheses.
3. All dollar values are in 1990 constant dollars.

One obvious change is the reduction in roadway collision rate, which was from 3.9 per million VMT in 1990 to 3.4 per million VMT in 2006.

Comparing rural and urban highways, there appears to be no significant difference in collision rate per vehicle-mile of travel. However, the VOC and travel time per VMT are marginally higher in urban areas than those in rural areas. The finding for vehicle emission rate per VMT is the contrary: the rate in rural areas is higher. This result is not unexpected because higher levels of congestion in urban areas lead to a higher travel time per unit mile. Also, more frequent speed changes in urban areas result in higher rates of fuel and oil use and greater wear and tear of engine parts and tires, leading to higher VOC per unit vehicle-mile compared with that in rural areas. However, average travel speed in rural areas is generally higher than that in urban areas. As average speed increases beyond a certain limit, a higher speed will bring a higher vehicle emission rate. As the share of VOC and value of travel time together constitutes 60 percent of the total highway user costs, urban highways in Indiana experience higher total highway user costs.

For interstate and non-interstate highways, there is no significant difference in collision rate per vehicle-mile of travel. The VOC and vehicle emission rate per VMT are marginally higher for interstates than those for non-interstate highways. However, the travel time per vehicle-mile of travel is slightly higher for non-interstate highways. The result is quite intuitive; average travel speed is relatively higher for interstate highways compared to that for non-interstates. As average speed increases beyond a certain limit, higher fuel, oil consumption, and vehicle emission rates are observed. Therefore, interstate highways are associated with a higher VOC and vehicle emission rate, but lower travel time per vehicle-mile of travel. As the share of VOC and vehicle emission costs together consists of 65% of the total highway user costs, interstate highways in Indiana experience higher highway user costs.

User Cost Models

Model coefficients obtained for vehicle operating costs, travel time, roadway collisions, vehicle emissions, as well as total user costs are as expected. For a given level of travel speed, deterioration in system condition can be expected to result in a higher level of unit costs for vehicle operation, causing increased unit highway user costs. Also, with no change in system condition, higher travel speed is associated with a reduction in travel time. Increase of travel speed up to a certain level is generally associated with a reduction in VOC, and beyond the limit will result in a higher vehicle emission rate. However, higher travel speed may increase the likelihood of roadway collisions. It appears, therefore, that an increased speed up to a certain level would reduce VOC. travel time and total highway user costs per vehicle-mile of travel on Indiana's state highways.

Conclusion

The present paper determines the unit values and trends in various highway user cost components for each functional class on Indiana's state highway network and finds that, on the average, highway user costs for each vehicle-mile of travel on Indiana state highways increased slightly over the years: $0.82 per VMT in 1990 and $1.01 per VMT in 2006 (both expressed in 1990 constant dollars). The paper goes further by using maximum likelihood estimation techniques to develop a set of statistical models for various highway functional classifications. The model results showed that factors that significantly affect network-level user costs are related to the physical condition and operational characteristics (travel speed). The paper, therefore, establishes empirical relationships between highway physical and operational characteristics on one hand and associated user costs on the other hand. This information is useful for planning, evaluating, and selecting highway investments or policies (such as change in speed limits, increases or decreases in funding for pavement preservation, etc.) that have an impact on highway physical and operational characteristics.

The developed user cost models enable determination of the operational costs of a highway system from the demand perspective at any given time. Secondly, such user cost models facilitate monitoring and evaluation of the cost-effectiveness of any improvement action. Furthermore, network-level user costs estimated using the developed models would facilitate comparison of the network impacts of alternative actions or policies within each management system or across management systems. In summation, the developed network-level user cost models provide policy makers and planners with a quick and easy method for estimating network-wide user impacts of investments.

Acknowledgements

The authors are grateful to the Joint Transportation Research Program (JTRP) at Purdue University and the Indiana Department of Transportation for the financial support of the project titled "Methodology for the Development of a Highway Asset Management System for Indiana." The authors are, however, responsible for the results of this study. This paper does not necessarily reflect the views of the project sponsors.

References

1. Sinha, K.C. and Fwa, T.F., (1989). On the Concept of Total Highway Management, *Transportation Research Record*, No. 1229, pp. 79-88.
2. FHWA, (1999). Asset Management Primer, *FHWA-IF-00-010*, Office of Asset Management, Federal Highway Administration, U.S. Department of Transportation, Washington, DC, USA.
3. AASHTO, (1977). *A Manual on User Benefit Analysis of Highway and Bus-Transit Improvements*, User's Manual of NCHRP 2-12 Project, "Highway User Economic Analysis," American Association of State Highway and Transportation Officials, Washington, DC, USA.
4. AASHTO, (2003). *User Benefit Analysis for Highways*, User's Manual of NCHRP 02-2 Project, "User Benefit Analysis for Highways," American Association of State Highway and Transportation Officials, Washington, DC, USA.
5. TTI, (TTI,) (1993). *MicroBENCOST User's Manual*, User's Manual of NCHRP 7-12 Project, "Microcomputer Evaluation of Highway User Benefits," Texas Transportation Institute, Texas A&M University, College Station, TX, USA.
6. Lewis, D., (2001). *HLB* Decision Economics, (Economics,) *NCHRP Project 2-18(3): Development of an Innovative Highway User-Cost Estimation Procedure and NCHRP Project 2-18(4): Development and Demonstration of StratBENCOST Procedure*, Silver Spring, MD, USA.
7. WRA, (2000). *Highway Development and Management HDM-4, Volume 3: Software User Guide*.(*Guide,*) World Road Association, Paris, France.
8. FHWA, (2000). *Highway Economic Requirements System User's Guide, FHWA-IF-02-059*, Federal Highway Administration, U.S. Department of Transportation, Washington, DC, USA.
9. Ozbay, K, Bartin, B., and Berechman, J., (2001). Estimation and Evaluation of Full Marginal Costs of Highway Transportation in New Jersey. *Journal of Transportation and Statistics*, Bureau of Transportation Statistics, U.S. Department of Transportation, Washington, DC, USA, pp. 81-103.
10. Li, Z. and Madanu, S., (2009). Highway Project-Level Life-Cycle Benefit/Cost Analysis under Certainty, Risk, and Uncertainty: A Methodology with Case Study, *Journal of Transportation Engineering*, 135(8), pp. 516-526.
11. Labi, S., Lamptey, G., and Li, Z., (2008). Decision Support for Optimal Scheduling of Highway Pavement Preventive Maintenance within Resurfacing Cycle, *Journal of Decision Support Systems,* 46(1), pp. 376-387.
12. McFarland, W.F., Memmott, J.L., and Chui, M.L., (1993). *Microcomputer Evaluation of Highway User Benefits*, Texas A&M University, College Station, TX, USA.
13. FHWA, (2001). Traffic Monitoring Guide. *FHWA-PL-01-021*, Federal Highway Administration, U.S. Department of Transportation, Washington, DC, USA.
14. Whitford, R.K. and Opsuth, J.L., (1996). Congestion Estimates for Indiana State Highway System. *Joint Transportation Research Program Report FHWA/A/IN/JHRP 96/8*, Purdue University, West Lafayette, IN, USA.
15. FHWA, (1985). Traffic Control Systems Handbook. *FHWA-IP-85-11*, Federal Highway Administration, U.S. Department of Transportation, Washington, DC, USA.
16. FHWA, (1992). *Costs of Air Pollution Abatement Study*, *FHWA-RD-92-068*, Federal Highway Administration, U.S. Department of Transportation, Washington, DC, USA.
17. Econometric Software, Inc., (2002). *LIMDEP8.0 User's Guide*, SAS Institute Inc., Econometric Software, Inc., Plainview, NY, USA.

Metric Conversion Factors

When You Know	Multiply by	To Find
inches (*in*)	2.54	centimeters (*cm*)
miles (*mi*)	1.61	kilometers (*km*)

Notation

AADT	Annual Average Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
DOT	Department of Transportation
FHWA	Federal Highway Administration
HDM-4	Highway Development and Management System(HDM-4)
HERS	Highway Economic Requirements System
HPMS	Highway Performance and Monitoring Systems
IRI	International Roughness Index
INDOT	Indiana Department of Transportation
ISOHDM	International Study of Highway Development and Management Tools
JTRP	Joint Transportation Research Program
NHTSA	National Highway Traffic Safety Administration
ORMC	One-Route Marginal Cost
PDO	Property Damages Only
PPI	Producer Price Index
SAS	Statistical Analysis Systems Software
TRB	Transportation Research Board
TSP	Total Suspended Particles
TTI	Texas Transportation Institute
VMT	Vehicle Miles of Travel
VOC	Vehicle Operating Costs
WPI	Wholesale Price Index