An Empirical Analysis of the Pricing Structure of Toll Facilities Based on Social Costs of Driving by Vehicle Class and Its Effects on Traffic, Toll Revenue, Emission, and ESAL

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Abstract

This study develops an analytical method to obtain toll rates for thirteen vehicle classes for seven toll facilities in Maryland, taking into account various social costs of driving automobiles. The model is comprised of two parts: (1) an equilibrium model to obtain non-peak period tolls that incorporates capital and maintenance costs of toll facilities, vehicle emission costs, and operating/maintenance costs incurred to vehicles due to uneven road surface, and (2) a model to estimate optimal congestion tolls for three facilities that currently experience congestion. The models are not a simple forward-moving model, but instead take into account the feedback effects of revised toll rates on traffic volume and social costs of driving.

The analysis results show some expected results in the estimated tolls and their effects on vehicle traffic, toll revenue, emission, and ESAL. While congestion tolls clearly show positive effects across three facilities, results related to estimated non-peak period tolls and their effects are not consistent across all facilities, depending on the relative magnitude of each social cost factor as well as the relative levels of current tolls. Results from the sensitivity analysis generally support the main results. These results reveal a lack of clear pattern in the current toll structure in relation to vehicle classes among facilities, and indicate possible cross-subsidies among facilities as well as among vehicle classes. Further research is warranted in order to achieve road pricing schemes that are more efficient and equitable.

1. INTRODUCTION

In recent years, the difficult situation of transportation finance in the US has led to policy discussion, debate, and propositions, in which elected officials focus primary on fiscal issues in the policy arena. On the other hand, the literature of transportation economics and travel behavior directs us to a notion that pricing for the use of transportation infrastructure and services, such as fuel tax, vehicle registration fee, bridge toll, and congestion toll, can influence travel behavior as individuals respond to a change in their travel costs. This change in travel behavior affects traffic flow and thus the costs associated with providing and maintaining transportation infrastructure and services. A socially optimal level of vehicle travel is one in which the individual, or other responsible party, fully internalizes the costs that are associated with their travel. Assessing the full cost of vehicle travel on the individual would modify travel behavior and ensure that a socially optimal level of vehicle travel is achieved. Narrowing the gap between the price individuals pay and the full cost that driving imposes on society will result in a more efficient use of roadway, travelers' time and other resources.

A number of studies in the past few decades have analyzed the social costs of motor vehicle use. However, few of these have considered road pricing which accounts for the large variation in social costs that different vehicle classes impose. The few studies that partially address this issue are limited to theoretical and simulation studies, rather than empirical studies. In order to fill this gap in research, this study has two main objectives: (1) finding a pricing structure based on a variety of social costs by vehicle class, taking into account changes in vehicle traffic in response to new prices, and (2) examining the total effects of the changes in pricing and in vehicle traffic. Specifically, the study develops an analytical model comprised of two stages. The fist stage is an equilibrium model to compute non-peak period tolls for thirteen vehicle classes for five bridges and two tunnels in Maryland, incorporating capital, maintenance, and other costs of toll facilities, environmental costs associated with vehicle emissions, and operating/maintenance costs that are incurred to vehicles by driving on uneven road surface. The second stage is a model to estimate optimal congestion tolls for three facilities, taking into account social costs in travel time delay caused by congestion. The models also take into account the feedback effects among traffic volume, social costs of driving, and toll rates.

This paper is organized as follows. Following this introduction, Section 2 provides a brief overview of road pricing and methods used to estimate the costs of driving. Section 3 provides a description of data and data sources, and Section 4 presents the general economic models developed with flow-charts. Section 5 presents and discuss analysis results. The effects of estimated toll rates for each of the seven facilities are examined in terms of changes in traffic volume, toll revenue, vehicle emissions, and the total number of ESAL. Section 6 briefly discusses results from the sensitivity analysis, varying values of a few key parameters in the models. The paper concludes with a summary of findings and a discussion of the implications of our findings for road pricing policies and suggestions for future work.

2. LITERATURE REVIEW

Road pricing has a long history. Adam Smith argued in "[t]he Wealth of Nations" (Smith 1937) that carriages passing over a highway or a bridge should pay a toll in proportion to their weight and for the maintenance cost in proportion to the wear and tear they caused. Pigou (1920) introduced the idea of a congestion toll on public roads, which is a differential taxation imposed on one of two parallel roads to achieve a social optimum in terms of total travel time for all road users. With a dramatic increase in vehicle traffic and congestion in the 1960s, the application of marginal-cost pricing began to gain wide support among transportation scholars. Vickery wrote extensively on marginal-cost pricing and traffic congestion (Vickrey 1963, 1968, 1969). Mohring and Harwitz (1962) extended the discussion to infrastructure provision, showing that the revenue from short-run marginal cost pricing is only sufficient to pay for the optimal capacity under the assumption of constant return to scale. Among other directions in which road pricing research has been extended was to add road damage cost to congestion cost to derive the optimal price (Newbery, 1988 and 1989; Small and Winston, 1988; Small et al. 1989). Other important extensions include the developments of dynamic models and models for heterogeneous users and for multi-modal networks (Arnott and Kraus, 1998; Verhoef, 2002; Verhoef and Small, 2004; Chen and Bernstein, 2004; de Palma et al., 2005; Gentile et al., 2005). In particular, Dafermos (1973) developed a theoretical model to determine toll patterns for multiclass-user transportation networks such that the user-optimizing flow pattern coincides with the system-operating pattern. In a network pricing optimization problem in the multi-user multimodal stochastic traffic assignment model, Bellei et al. (2002) proved the validity of marginal pricing principle in determining tolls along with the social welfare as an objective function. De Palma and Lindsey (2004) obtained optimal tolls that take into account variations among vehicles in the effects of different values of passenger car equivalency (PCE) on congestion and value of time. Chu and Tsai (2004) obtained tolls that should vary by vehicle type because of the varying degree of damage on the highway cased by each vehicle type. However, these studies simplify the real-world situation substantially by categorizing vehicle classes into a very few groups. Such simplification tends to result in an overestimation for large trucks with respect to the externalities they produce and underestimation for passenger cars (Chu and Tsai 2004).

The Federal Highway Administration (FHWA) has conducted a series of highway cost allocation studies (HCAS) that take into account a relatively larger variation of vehicle type in order to estimate costs associated with the use of road infrastructure (FHWA 1997). Fu and Schwartz and Fu, Schwartz and Broadwater (2007, 2010) refined the HCAS method to estimate new toll rates for facilities in Maryland, and found that two-axle vehicles are currently overcharged for the costs they incur, while five-axle trucks are currently undercharged.

Only a few road pricing studies have incorporated various social costs of the externalities produced by vehicle traffic beyond roadway infrastructure costs. Ozbay, Bartin and Berechman (2001) developed a model to estimate the network-wide full marginal transportation costs of driving a particular driving route on highway in New Jersey, including various costs, but did not consider a change in vehicle traffic caused by imposing new pricing. Holguin-Veras and Cetin (2009) computed optimal tolls for multiclass vehicle traffic while accounting for environmental, pavement and congestion cost.

In summary, although many studies indicate that the social costs of driving substantially vary by class of vehicle, little empirical research on the subject of road pricing has been conducted to fully take into account this variation, include various types of social costs of driving, and incorporate the feedback effects among traffic volume, social costs of driving, and road pricing in an analysis of the relationship between vehicle heterogeneity and optimal toll rates as well as the effects of optimal tolls.

3. DATA AND DATA SOURCES

Table 1 shows basic information on all seven toll facilities— five bridges and two tunnels—in Maryland examined in this study.

Table 1 Information for the Seven Toll Facilities Examined in the Study

Full Name and Abbreviation	Route	SHA District	Functional Class	Number of lanes	Length (miles)	Structure	Free-flow Speed (mile/hour)
Thomas J. Hatem Memorial Bridge (TJH)	US 40	2 & 4	14	4	1.3	Bridge	55
					0.5	Highway	
John F. Kennedy Memorial Highway (JFK)	I-95	2 & 4	01 & 11	6	1	Bridge	70
				6	32	Highway	
				8	17	Highway	
Fort McHenry Tunnel (FMT)	I-95	4	11	8	1.5	Tunnel (4 Bores)	70
				8	11.5	Highway	
Baltimore Harbor Tunnel (BHT)	I-895	4	11	4	1.75	Tunnel (2 Bores)	65
				4	15.9	Highway	
Francis Scott Key Bridge (FSK)	I-695	4	12	4	1.6	Bridge	65
				4	8.7	Highway	
Governor Harry W. Nice Memorial Bridge (HWN)	US 301	5	02	2	1.7	Bridge	55
William Preston Lane, Jr. Bridge (WPL)	US 50	5	12	3	4.33	Bridge	55
				2	4.35	Bridge	

Note: The seven facilities in the study belong to five different road functional class: (1) rural interstate, (2) rural other principle arterial, (11) urban interstate, (12) urban other freeway and expressway and (14) urban other principle arterial.

While most data used for the purpose of this study are publicly available, several sets of data and information were obtained from Maryland Transportation Authority (MdTA) and Maryland State Highway Administration (SHA) through direct communication. MdTA's financial statements provided vehicle traffic volume data in six categories of the number of axle for the toll facilities. Basic information on each toll facility, such as number of lanes, traffic capacity, free flow speed, annual average daily traffic, and annual average daily truck traffic, construction and other cost data for the toll facilities were also obtained from MdTA. An estimate of pavement cost per mile was obtained from SHA. Percentage of vehicle traffic volume by vehicle class was also obtained from SHA for different functional classes of roadways for the entire state of Maryland. SHA's *Pavement Design Guide* shows the traffic land distribution factor for different number of lanes, and SHA Internet Traffic Monitoring System provides detailed hourly traffic count data by vehicle class for selected locations on the interstate and state highways.

Data used to calculate the single axle load for each vehicle class was taken from FHWA HCAS tool including information on axle configuration, axle weight distribution, and vehicle weight distribution (FHWA 1997). Twenty FHWA vehicle classes in HCAS were re-categorized into the thirteen vehicle classes in this study, following SHA's vehicle categories for traffic volume data (Table 2). Parameters for overall load equivalency factors (LEF) by road functional class are used to convert physical axles to ESALs. Passenger Car Equivalency (PCE) for different operating gross weights (OGW) and for road functional classes for 20 FHWA vehicle classes were re-categorized to obtain one PCE value for each of the 13 vehicle classes.

Table 2 Vehicle Class used by FHWA and SHA, Maryland

Maryland			FHWA
Class 1	MOTORCYCLES		Auto
Class 2	PASSENGER CARS	2 AXLES 4 TIRES	Auto
Class 3	LIGHT TRUCKS OTHER	2 AXLES 4 TIRES	LT4
Class 4	BUSES		Bus
Class 5	SINGLE-UNIT TRUCKS	2 AXLES 6 TIRES	SU2
Class 6	SINGLE-UNIT TRUCKS	3 AXLES	SU3
Class 7	SINGLE-UNIT TRUCKS	4 OR MORE AXLES	SU4+
Class 8	SINGLE-TRAILER TRUCKS	4 OR LESS AXLES	CS3, CS4, CT34
Class 9	SINGLE-TRAILER TRUCKS	5 AXLES	CS5T, CS5S, CT5
Class 10	SINGLE-TRAILER TRUCKS	6 OR MORE AXLES	CS6, CS7+, CT6+
Class 11	MULTI-TRAILER TRUCKS	5 OR LESS AXLES	DS5
Class 12	MULTI-TRAILER TRUCKS	6 AXLES	DS6
Class 13	MULTI-TRAILER TRUCKS	7 AXLES	DS7, DS8, TRPL

Data on emission rates (g/mile) for five pollutants are obtained from the 1997 HCAS. Estimates of social costs of pollutants in vehicle emissions are obtained from McCubbin and Delucchi (1999) for 1991. More details are provided in the later section. Value of time (VOT) is obtained from the Maryland Statewide Transportation Model (MSTM) at National Center for Smart Growth Research and Education (NCSG). Two different values of VOT are 46.32 cents per minute ($27.79 per hour) for passenger cars and 106.4 cents per minute ($63.84 per hour) for trucks in 2011 dollars.[1]

In regard to additional maintenance and operating costs for vehicles due to poor road conditions, vehicle operating costs including fuel consumption, tire wear and repair and maintenance costs are obtained from the study by National Cooperative Highway Research Program Report 720 (Chatti and Zaabar 2012), in which additional costs are computed between the base line condition (international roughness index, IRI = 1) and the condition (IRI = 3) for five different vehicle categories—medium car, van, SUV, light trucks, and articulated truck for two different operating speeds (55 and 70 miles per hour).

4. MODEL DEVELOPMENT

While the current toll structure in Maryland is based on the number of axles, our analysis estimates toll rates for thirteen FHWA vehicle classes, taking into account vehicle configuration, weight, number of axles and five social costs imposed by driving. An approach to calculate each social cost is discussed below. Costs for accidents are not included as past studies on the subject showed no difference in cost per vehicle mile between passenger cars, trucks, and trailers.

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[1] These values are considered reasonable, compared to estimated VOTs for trucks in several studies, including Smalkowski and Levinson (2005) and Forkenbrock and March (2005).

4.1 Marginal Maintenance Cost

Marginal maintenance cost was derived from the model developed by Small et al. (1989). In this framework, each vehicle in class i contributes as much to road wear as l_i single axles weighing 18,000 pounds: it is said to have l_i equivalent single-axle loads (ESAL). Load equivalency factors (LEFs) are used to convert physical axles to ESALs for each vehicle by eq. (1):

$$l_i = \sum_{j=1}^{n} LEF_j = \sum_{j=1}^{n} a_j W_j^{b_j} \qquad \text{--- eq. (1)}$$

where

j is the axle group,

W_j is the load level for the axle group,

a_j and b_j are the coefficients for the axle group's type, and

n is the total number of axle groups of the vehicle.

1997 HCAS provides multiple sets of parameters (*a* and *b* in eq. (1)), which varies by pavement type and road functional class and distress type, to calculate LEF for each vehicle class: (1) the overall values and (2) the state-specific values. In this study, we use the overall values.

Then, considering a one-mile, one-directional stretch of highway of width W (number of lanes) and depth D, short-run marginal cost of traffic loadings at any level of D that can be attributed to vehicle i ($SRMC_i$) is obtained as eq. (2):

$$SRMC_i = \frac{\partial(m+k)}{\partial Q_i} = r\frac{\partial M}{\partial Q}\frac{\partial Q}{\partial Q_i} = l_i \frac{\alpha\beta C(W)\lambda}{N} \qquad \text{--- eq. (2)}$$

where

m is annualized highway maintenance cost,

k is annualized highway capital cost,

M is the present discounted value of all required highway maintenance expenses,

Q is defined as annual traffic loading $Q = \sum_i l_i Q_i$,

Q_i is traffic of passages by vehicles in class i,

r is the interested rate,

N is the total number of ESAL that pass over a segment of highway during the constant resurfacing interval, T (=15 years in this study),

C(W) is the resurfacing costs per mile,

λ is the traffic land distribution factor.

$$\alpha = \frac{(rT)^2 e^{rT}}{(e^{rT}-1)^2}, \beta = \frac{e^{mT}}{1+mT} \qquad \text{--- eq. (3)}$$

$$T = \frac{N(D)}{\lambda Q} e^{-mT} \qquad \text{--- eq. (4)}$$

The basic idea here is that each vehicle with l_i has the responsible cost $SRMC_i$ in proportion to the ratio of l_i to N or N(D). Marginal maintenance cost part of toll rate is calculated by multiplying SRMC by the roadway distance of each facility in the MdTA's jurisdiction.

4.2 Environmental Cost

Marginal environmental cost ($/mile) is calculated taking into account five types of pollutants: particulate matter (PM_{10}), volatile organic compound (VOC), carbon monoxide, nitrogen oxides (NO_x) and sulfur oxide (SO_x). For each type of pollution, the cost per VMT ($/mile) is obtained as the product of marginal environmental cost ($/kg) from the study by McCubbin and Delucchi (1999) and the emission rate (g/mile) at the speed of 55mph from the 1997 HCAS study (FHWA, 1997). Summing up the costs per mile for all five pollutants and multiplying by the distance of facility, the total marginal environmental cost ($) is calculated for each facility. In this study, motorcycles and passenger cars are treated as light-duty gasoline vehicles; light truck (4 tires) and buses are treated as light-duty gasoline truck; all the other trucks are considered as heavy-duty diesel trucks, which have gross vehicle weight over 8,501 pounds. All the costs are adjusted in 2011 dollars in the analysis.

4.3 Marginal Operating Cost

Marginal operating cost was also derived from the model developed by Small et al. (1989). The present value of total user cost over the first cycle is obtained through:

$$P_0 = \int_0^T V_0\, e^{gt} v(t) e^{-rt} dt \qquad \text{--- eq. (5)}$$

where, v(t) is the average user cost, $V_0 e^{gt}$ is equal to traffic volume in year t and g is a constant annual growth rate.

The sum of the present value of total user cost over many cycles, assuming r>g, is

$$U = \frac{P_0}{1-e^{-(r-g)T}} = \frac{V_0}{1-e^{-aT}} \int_0^T v(t) e^{-at}\, dt \qquad \text{--- eq. (6)}$$

where a=r-g. In this study, g is assumed to be zero.

$$v(t) = v_0 + v_1 (\frac{t}{T})^5 \qquad \text{--- eq. (7)}$$

where v_0 is the user cost on a new pavement, and $(v_0 + v_1)$ is the user cost on a pavement at quality π_f. T is a function of the traffic volume Q, given by eq. (4) in the previous section.

From these, the marginal operating cost for each vehicle class is obtained as:

$$MC_{oi} = r \frac{dU}{dT} \frac{dT}{dQ} \frac{dQ}{dQ_i} \qquad \text{--- eq. (8)}$$

4.4 Construction and Other Capital Cost

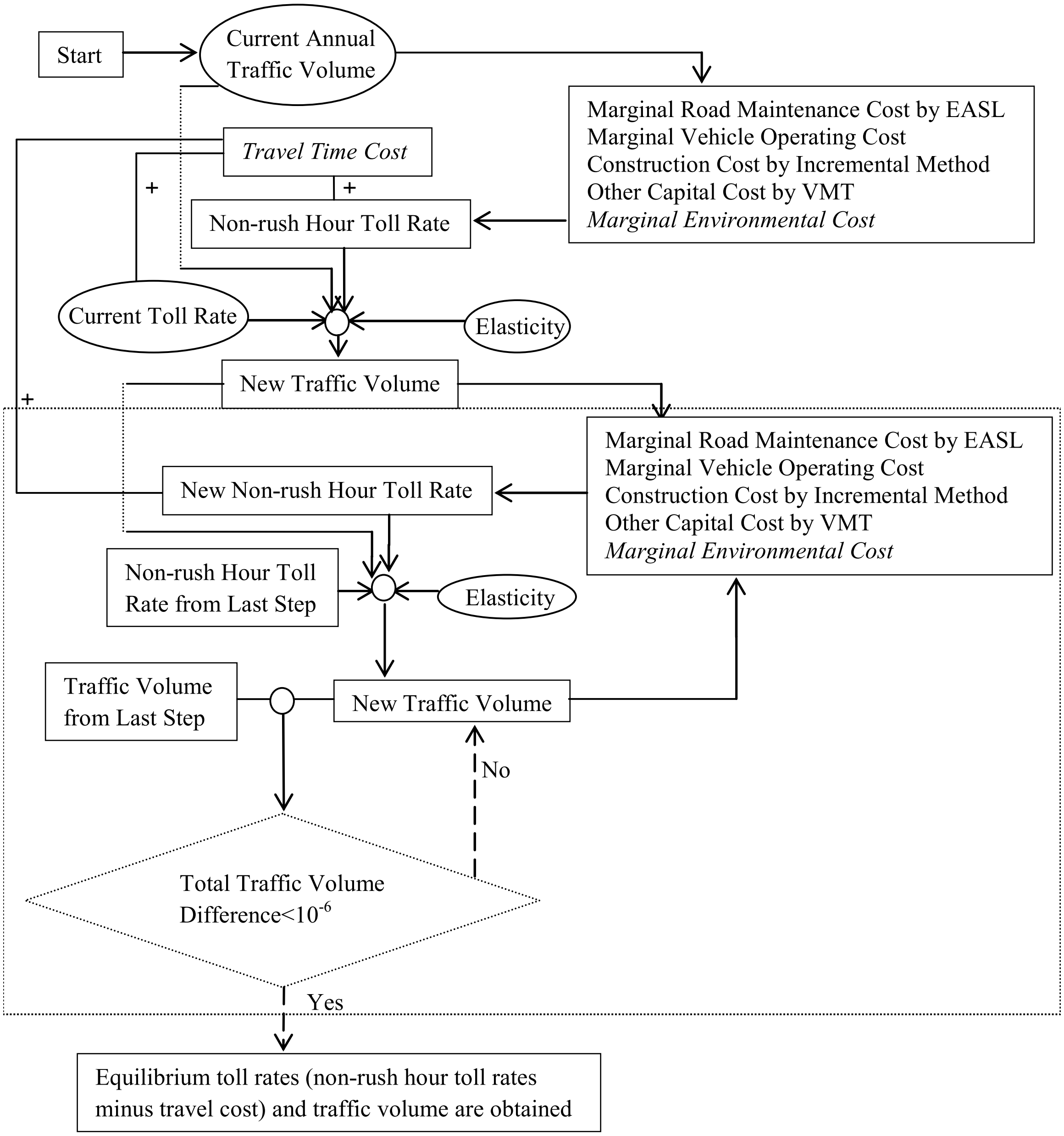
Construction cost for bridges are allocated to different classes of vehicle with different levels of loading and weight, using the incremental method from 1997 HCAS study that takes into account what level of design loading is required in the bridge design to accommodate each type of vehicle (FHWA 1997). Construction cost data are available only for four bridges (HWN, JFK, WPL and TJH), all of which are over 55 ft and designed to HS 20 loading. In addition, other capital costs are allocated to the thirteen vehicle classes based on the VMT.

Procedure to Obtain Optimal Toll Rates at Equilibrium

Optimal toll rates were obtained in a two-step process where the change to traffic volume in response to revised toll rates by vehicle class was accounted for. The first-stage of analysis (Figure 1 (A)) assumes an interest rate (r) of 6 percent, constant maintenance interval (T) of 15 years, constant elasticity values of -0.05 and -0.01 for passenger cars and trucks respectively, and LEF values from FHWA's Highway Cost Allocation Study in 1997 to obtain initial toll rates during non-peak hours. As toll rates change so does traffic volume, as road users respond to a change in their travel cost. Depending on values for elasticity, which is applied to the total sum of the baseline operating cost, travel time cost, and toll rates, and different levels of toll change, the magnitude of change in traffic volume varies among different vehicle classes. This results in a different distribution of traffic volume by vehicle class after the toll change.

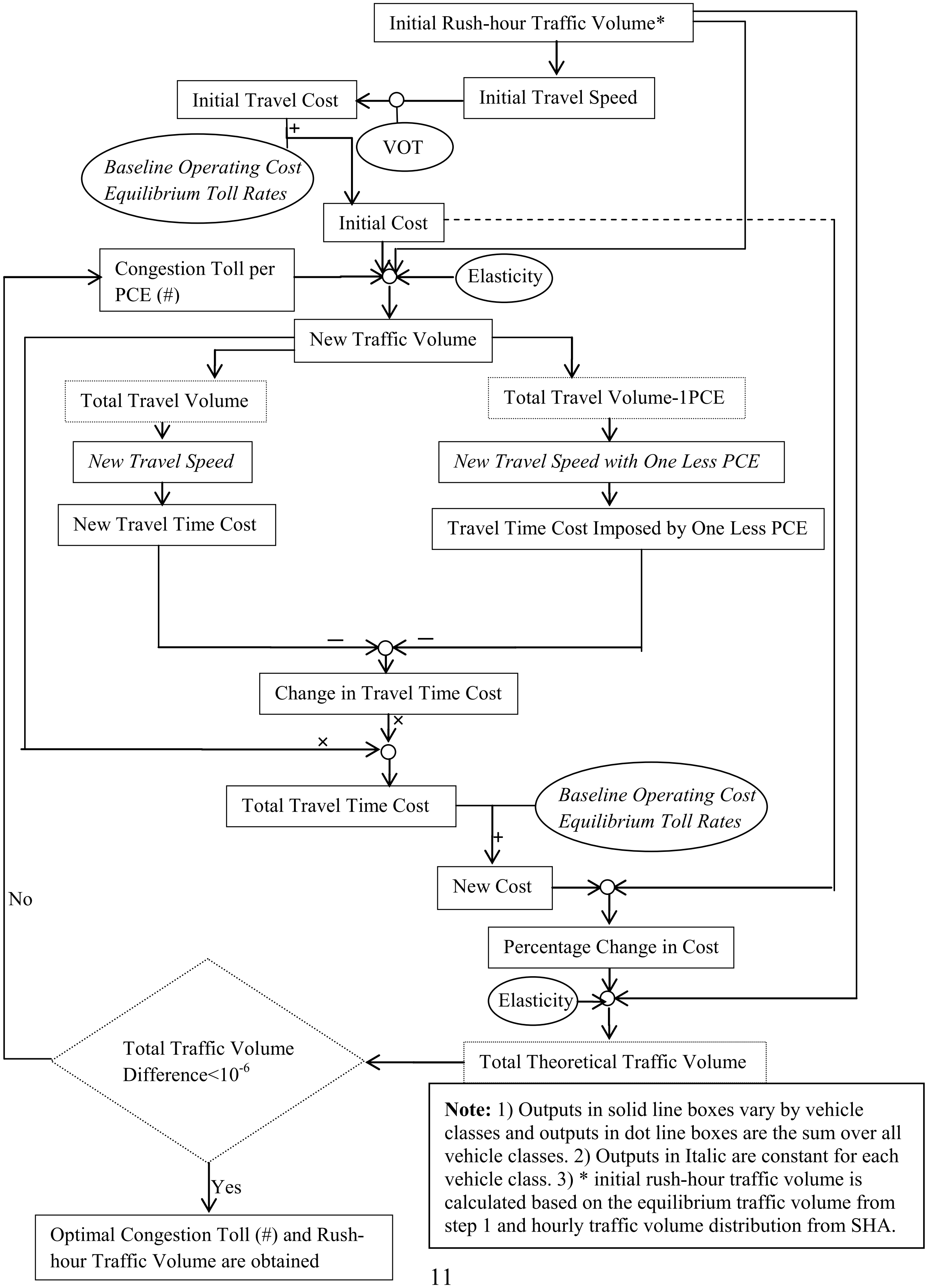
In turn, new traffic volume by vehicle class affects the social costs each vehicle trip is responsible for in its usage of facility because all the costs except environmental costs are *a function of traffic volume*. With one set of toll rates by vehicle class in each iteration, new non-peak-hour traffic volume is obtained to result in another set of toll rates. When the total traffic volume and the distribution of traffic become stable, the equilibrium can be found with non-peak hour toll rates and corresponding traffic volumes by vehicle class.

Figure 1 (A) Equilibrium Non-rush Hour Toll Model



In the second step, the equilibrium traffic volume in non-peak hours from the first step, rather than traffic volume based on the 24-hour distribution, is used to calculate optimal congestion cost with an assumption that the congestion toll rate influences the *distribution* of traffic among 24 hours of a day, but not the total daily traffic volume (Figure 1 (B)). The optimal congestion cost or toll is defined as the difference between individual travel cost and social travel cost. The peak-hour toll rate is then defined as the sum of non-rush hour toll rate and congestion toll. Details in the procedure are explained in the next section on congestion cost.

Figure 1 (B) Optimal Congestion Toll Model



Note: 1) Outputs in solid line boxes vary by vehicle classes and outputs in dot line boxes are the sum over all vehicle classes. 2) Outputs in Italic are constant for each vehicle class. 3) * initial rush-hour traffic volume is calculated based on the equilibrium traffic volume from step 1 and hourly traffic volume distribution from SHA.

4.5 Congestion Cost

The optimal congestion cost estimation method in this study is an extension of the model developed by Roth and Villoria (2001). Congestion cost is computed for BHT, FMT, and WPL, the only facilities which showed periods of congestion, using equations provided by the Highway Capacity Manual that determine vehicle traffic speed based on a given free-flow speed (FFS) and available flow data (flow rate V_p in eq. (9)). The maximum hourly traffic volume (V_p) was identified based on annual traffic volume and the hourly traffic distribution and used in the procedure, which is described below.

1. V_p is combined with the proportion of each class of vehicle in the total traffic to calculate the initial number of vehicles in each of the thirteen vehicle classes.
2. Calculate the initial traffic speed for the initial traffic flow obtained in step 1, using eq.(9) and eq. (10) that relates traffic speed and flow defined as in the Highway Capacity Manual (Exhibit 23-3):

$$V_p = \frac{V}{PHF \times N \times f_{Hv} \times f_p} = \frac{\sum_{i=1}^{n} Q_i E_i}{PHF \times N \times f_p} \qquad \text{--- eq. (9)}$$

$$S = FFS - [\frac{1}{28}(23FFS - 1800)(\frac{V_p + 15FFS - 3100}{20FFS - 1300})^{2.6}] \qquad \text{--- eq. (10)}$$

where
V_p: 15-minute passenger car equivalent flow rate (vehicle per hour per lane)
V: hourly volume (vehicles/hour)
PHF: Peak-hour factor from Highway Capacity Manual
N: number of lanes
f_p: driver population factor (=1.0 in this study)
f_{HV}: heavy vehicle adjustment factor as expressed as:

$$f_{Hv} = \frac{1}{1 + \sum_{i=1}^{n} P_i(E_i - 1)} \qquad \text{--- eq. (11)}$$

where
E_i: PCE for class i vehicle
P_i: proportion of class i vehicle in traffic stream,

$$P_i = \frac{Q_i}{V} \qquad \text{--- eq. (12)}$$

$$V = \sum_{i=1}^{n} Q_i \qquad \text{--- eq. (13)}$$

Q_i: number of class i vehicles in traffic stream
V: total vehicle number,
n: number of vehicle classes, that is, 13 in this study

3. The initial travel time cost for each vehicle to travel one km (C_i) on a facility is calculated by taking an inverse of the initial traffic speed multiplied by value of time. This is combined with the baseline operating cost to calculate the initial travel cost.
4. An initial value of variable congestion charge is introduced and added to the initial travel cost in Step 3 to obtain the total travel cost, which varies by vehicle class.
5. Calculate the new traffic volume by vehicle class, applying the assumed elasticity and the total travel cost in Step 4 to V_p in Step 1.

6. Calculate the new total traffic volume, the new traffic composition based on traffic volume values in Step 5, the new value of V_p using eq. (9), and the new traffic speed using eq. (10).
7. Calculate the total cost to travel one km (C_1) based on the updated speed in Step 6 just like in Steps 2 and 3.
8. Calculate another value of V_p with one less PCE per lane per hour (Step 6) and also the total cost to travel one km (C_2) at a slightly higher speed.
9. Calculate the difference between C_1 and C_2 , and then multiplying it by the total traffic volume to estimate the travel time delay cost (C_T) imposed by one PCE on other vehicles.
10. Using (C_i), calculate an average cost weighted by the new traffic composition from Step 6, and compare this with C_T to calculate a percentage change in cost.
11. Calculate the "theoretical flow," using the initial flow (Step 1), the percent change (Step 10), and the assumed elasticity.
12. Calculate the "theoretical cost" by multiplying the weighted average cost (step 10) by one plus the percent change.
13. Check the difference between the "theoretical flow" and the flow after imposing the congestion charge (Step 5). If the difference is larger than the threshold value (10^{-6}), go back to Step 4 with a new value of congestion charge; if the difference is small enough ($<10^{-6}$), take the value of congestion charge as the optimal congestion cost per PCE per km.

For each vehicle class, congestion toll is calculated by multiplying the optimal congestion cost per PCE per km for each vehicle class and length of each facility.

5. ANALYSIS RESULTS

This section describes analysis results in terms of toll structure, traffic volume, toll revenue, vehicle emission, and ESAL.

5.1 Estimated Tolls

Table 3 (a), (b), and (c) show current toll rates, current annual traffic volume, estimated traffic volume, and percentage changes for the seven toll facilities. The seven facilities are categorized into three different groups, based on how the new tolls compare to the current tolls for different vehicle classes. For BHT and FSK, the estimated tolls are generally higher than the current toll rates for all vehicle classes, except Class 10 for FSK (Table 3 (a)), partly due to the total length of each MdTA facility—17.7 and 10.3 miles respectively. The portion of the toll that can be attributed to infrastructure, environmental, and vehicle operating costs increases as driving distance for each facility increases.

In examining the toll rate across vehicle classes, the rate for Class 10 (single-trailer truck with six or more axles) is lower than the estimated rate for Class 9 (single-trailer truck with five axles). This is opposite to the current tolls because Class 10 has more axles, lower LEF and lower weight per axle than Class 9, resulting in the less road damage and maintenance costs. Class 5 shows substantially higher estimated toll rates for all of the seven facilities. Class 5 includes SU2, which carries much more weight than a passenger car and LT4 but is charged the same toll as these two classes based on its two axles; this means that the current toll structure encourages the usage of vehicles with fewer axles but more weights. At the same time, the estimate toll rates for Class 5 are somewhat overestimated due to a lack of variance in environmental costs associated with heavy-duty vehicles, which include all vehicles with gross vehicle weight over 8,501 pounds and have much higher emission rates.

For JFK and FMT, the estimated tolls are substantially higher for Classes 5-9 and Classes 11-12 and lower for Classes 1-4 than the current tolls (Table 3 (b)). The current toll rates for Classes 5-9 and 11-12 are too low to cover their responsible costs, while other classes are paying more. In particular, as the current tolls for Class 11 are set based on five-axles, they still underestimate the responsible cost, lacking consideration of higher responsible costs based on higher weight per axle. The variation in toll rate change between vehicle classes indicate a cross-subsidy among different classes; this not only results in an efficiency loss but also in more road damage and environmental pollution caused by higher traffic volume by higher vehicle classes.

For TJH, WPL, and HWN, the estimated tolls are, in general, higher for lower vehicle classes (1-5) and lower for higher vehicle classes (6-13) than the current tolls, except a few cases (Table 3 (c)). In the cases of TJH and WPL, the higher toll rates for Class 11 can be explained in the same way as in the case of JFK and FMT. This indicates that higher vehicle classes are over-charged to cover the revenue loss from lower vehicle classes, which is not economically efficient. Our estimated toll rates are much higher than the current effective tolls for Class 1-5 vehicles for TJH for the following reason. In addition to 33 cent per trip for Classes 1-5, commuters pay only \$10 per year—about 5 cents per round trip, assuming five days a week for 40 weeks each year—under the current Automatic Vehicle Identification (AVI) program. As ninety percent of the traffic over five million vehicles per year today uses this program, TJH has achieves only \$2.8 million per year of toll revenue. While this low toll accommodates the travel needs of regular users, it does not work well from the financial perspective.

Estimated Tolls with Congestion Tolls

Total tolls including estimated congestion tolls are shown in Table 3 (d) for BHT, FMT, and WPL. Whenever congestion exists, the estimated tolls with congestion are higher than the estimated tolls in the first stage for all vehicles. The magnitude of congestion toll significantly varies by vehicle type because heavier trucks and trailers are slower in their acceleration and have a higher number of PCEs, resulting in a dramatic increase in congestion tolls for Class 4-13.

The variation in congestion tolls is also found by facility. BHT has much higher per lane traffic volume, which results in higher congestion costs and higher congestion tolls than FMT and WPL. Total tolls with congestion toll for Classes 10 and 13 of FMT and Classes 7-9 of WPL are lower than the current tolls, because of the substantially lower estimated tolls in the first stage.

Table 3 Toll Rates and Traffic Volume

(a) Toll Rates and Traffic Volume after the First Stage for BHT and FSK

	BHT						FSK					
	Current Toll	Estimated Toll	% Change	Initial Volume	Estimated Volume	% Change	Current Toll	Estimated Toll	% Change	Initial Volume	Estimated Volume	% Change
Class 1	1.13	1.75	54.72%	26,117	26,036	-0.31%	1.09	1.31	20.17%	8,636	8,619	-0.20%
Class 2	1.13	1.75	54.72%	10,595,524	10,562,930	-0.31%	1.09	1.31	20.17%	4,707,418	4,698,001	-0.20%
Class 3	1.13	2.23	97.13%	1,505,625	1,504,860	-0.05%	1.09	1.59	46.15%	763,458	763,116	-0.04%
Class 4	1.13	2.25	99.22%	91,408	91,361	-0.05%	1.09	1.87	71.24%	36,273	36,248	-0.07%
Class 5	**1.13**	**17.66**	**1463.27%**	271,613	269,536	-0.76%	**1.09**	**11.09**	**917.87%**	131,849	130,672	-0.89%
Class 6	6.00	17.63	193.80%	75,738	75,406	-0.44%	6.00	10.93	82.22%	24,182	24,108	-0.31%
Class 7	9.00	17.65	96.13%	18,282	18,228	-0.29%	9.00	11.09	23.18%	8,061	8,052	-0.11%
Class 8	9.00	17.71	96.73%	67,903	67,703	-0.30%	9.00	11.42	26.91%	24,182	24,151	-0.13%
Class 9	12.00	18.08	50.63%	373,468	372,770	-0.19%	12.00	14.39	19.94%	47,788	47,736	-0.11%
Class 10	15.00	17.93	19.51%	11,752	11,743	-0.08%	15.00	13.44	-10.40%	2,879	2,881	0.06%
Class 11	12.00	19.34	61.13%	10,447	10,423	-0.23%	12.00	22.53	87.74%	1,152	1,146	-0.48%
Class 12	15.00	18.70	24.67%	3,917	3,913	-0.10%	15.00	19.03	26.85%	-	-	-
Class 13	20.00	20.10	0.48%	7,835	7,835	-0.002%	20.00	27.38	36.89%	1,727	1,723	-0.24%
Total	-	-	-	13,059,629	13,022,743	-0.28%	-	-	-	5,757,606	5,746,453	-0.19%

(b) Toll Rates and Traffic Volume after the First Stage for FMT and JFK

	JFK						FMT					
	Current Toll	Estimated Toll	% Change	Initial Volume	Estimated Volume	% Change	Current Toll	Estimated Toll	% Change	Initial Volume	Estimated Volume	% Change
Class 1	4.60	3.28	-28.76%	30,750	30,865	0.37%	1.76	1.29	-26.47%	46,294	46,450	0.34%
Class 2	4.60	3.28	-28.76%	12,475,178	12,521,793	0.37%	1.76	1.29	-26.47%	18,781,430	18,844,647	0.34%
Class 3	4.60	4.17	-9.26%	1,772,724	1,772,941	0.01%	1.76	1.65	-6.41%	2,668,843	2,669,064	0.01%
Class 4	4.60	4.26	-7.41%	107,624	107,635	0.01%	1.76	1.67	-5.29%	162,029	162,040	0.01%
Class 5	4.60	33.12	620.02%	319,798	317,153	-0.83%	1.76	13.02	640.04%	481,456	477,473	-0.83%
Class 6	15.00	33.02	120.16%	89,174	88,814	-0.40%	6.00	12.99	116.55%	134,252	133,726	-0.39%
Class 7	23.00	33.09	43.88%	21,525	21,483	-0.19%	9.00	13.01	44.58%	32,406	32,343	-0.19%
Class 8	23.00	33.25	44.56%	79,949	79,793	-0.20%	9.00	13.07	45.17%	120,364	120,129	-0.19%
Class 9	30.00	34.42	14.74%	439,722	439,393	-0.07%	12.00	13.40	11.67%	662,003	661,614	-0.06%
Class 10	38.00	37.58	-1.10%	13,837	13,838	0.01%	15.00	13.27	-11.56%	20,832	20,846	0.06%
Class 11	30.00	41.70	39.00%	12,300	12,276	-0.20%	12.00	14.54	21.19%	18,518	18,498	-0.11%
Class 12	38.00	39.94	5.10%	4,612	4,611	-0.03%	15.00	13.97	-6.89%	6,944	6,947	0.04%
Class 13	50.00	43.91	-12.18%	9,225	9,232	0.08%	20.00	15.23	-23.84%	13,888	13,909	0.15%
Total	-	-	-	15,376,417	15,419,828	0.28%	-	-	-	23,149,258	23,207,686	0.25%

(c) Toll Rates and Traffic Volume after the First Stage for TJH, WPL, and HWN

	TJH						WPL						HWN					
	Current Toll	Estimated Toll	% Change	Initial Volume	Estimated Volume	% Change	Current Toll	Estimated Toll	% Change	Initial Volume	Estimated Volume	% Change	Current Toll	Estimated Toll	% Change	Initial Volume	Estimated Volume	% Change
Class 1	0.33	1.92	482.79%	16,732	15,691	-6.22%	2.07	2.17	5.02%	20,337	20,312	-0.12%	2.33	2.36	1.29%	13,945	13,939	-0.05%
Class 2	0.33	1.92	482.79%	3,993,786	3,745,420	-6.22%	2.07	2.17	5.02%	11,084,881	11,071,351	-0.12%	2.33	2.36	1.29%	2,442,781	2,441,626	-0.05%
Class 3	0.33	1.97	498.28%	799,568	794,251	-0.67%	2.07	2.29	10.85%	1,797,768	1,797,199	-0.03%	2.33	2.41	3.32%	633,994	633,880	-0.02%
Class 4	0.33	2.16	555.82%	28,900	28,562	-1.17%	2.07	2.54	22.51%	85,414	85,339	-0.09%	2.33	2.48	6.34%	22,788	22,768	-0.09%
Class 5	0.33	3.97	1102.56%	150,585	148,027	-1.70%	2.07	6.49	213.47%	310,474	308,452	-0.65%	2.33	4.02	72.36%	109,180	108,697	-0.44%
Class 6	7.21	3.82	-47.02%	26,365	26,472	0.41%	9.00	6.41	-28.79%	56,943	57,053	0.19%	9.00	3.99	-55.70%	24,489	24,615	0.51%
Class 7	17.37	3.93	-77.37%	6,591	6,648	0.86%	12.00	6.52	-45.69%	18,981	19,047	0.35%	12.00	4.03	-66.43%	5,102	5,136	0.66%
Class 8	17.37	4.27	-75.42%	20,788	20,960	0.83%	12.00	6.76	-43.71%	56,943	57,132	0.33%	12.00	4.09	-65.91%	21,768	21,910	0.65%
Class 9	23.83	7.27	-69.49%	23,323	23,499	0.75%	15.00	9.13	-39.11%	112,530	112,881	0.31%	15.00	4.77	-68.22%	112,922	113,703	0.69%
Class 10	38.00	25.16	-33.78%	2,028	2,035	0.34%	18.00	17.09	-5.07%	6,779	6,782	0.04%	18.00	9.42	-47.64%	7,823	7,860	0.47%
Class 11	23.83	35.98	50.98%	507	504	-0.50%	15.00	23.57	57.13%	2,712	2,699	-0.45%	15.00	11.13	-25.78%	2,721	2,728	0.24%
Class 12	38.00	31.09	-18.18%	507	508	0.18%	18.00	21.33	18.53%	-	-	-	18.00	10.60	-41.10%	680	683	0.40%
Class 13	50.00	42.28	-15.44%	1,014	1,016	0.15%	20.00	27.01	35.04%	4,067	4,055	-0.29%	40.00	12.03	-69.93%	3,061	3,083	0.72%
Total	-	-	-	5,070,693	4,861,398	-4.13%	-	-	-	13,557,829	13,542,303	-0.11%	-	-	-	3,401,255	3,400,625	-0.02%

(d) Total Estimated Tolls after the Second Stage, Congestion Tolls, and Congestion Savings for BHT, FMT and WPL

Facility	**BHT**	**FMT**	**WPL**	**BHT**	**FMT**	**WPL**
	Total Tolls with Congestion Tolls			**Congestion Tolls**		
Class 1	6.05	1.80	3.59	4.30	0.51	1.42
Class 2	6.05	1.80	3.59	4.30	0.51	1.42
Class 3	7.05	2.22	3.88	4.83	0.57	1.59
Class 4	10.24	2.61	5.17	7.99	0.94	2.63
Class 5	24.60	13.84	8.77	6.94	0.82	2.28
Class 6	25.62	13.94	9.04	7.99	0.94	2.63
Class 7	27.22	14.14	9.67	9.57	1.13	3.15
Class 8	26.05	14.05	9.50	8.34	0.99	2.75
Class 9	29.58	14.76	12.92	11.50	1.36	3.79
Class 10	30.31	14.73	21.17	12.38	1.46	4.08
Class 11	30.49	15.86	27.24	11.15	1.32	3.67
Class 12	30.91	15.41	25.36	12.21	1.44	4.02
Class 13	34.23	16.90	31.67	14.14	1.67	4.66
	Total Effects of Estimated Toll Rates			**Effects of Congestion Tolls**		
Hourly Rush-hour Traffic Change (# of vehicles)	-31.81	6.30	-21.13	-23.84	-5.69	-17.65
Travel Speed Change (km/hour)	0.65	-0.02	0.45	0.47	0.02	0.37
Tavel Time Savings (seconds)	9.38	-0.14	1.59	6.80	0.12	1.31
Delay Cost Savings ($/lane/hour)	130.26	-1.52	22.82	94.34	1.37	18.78

Note: Travel delay cost savings is calculated as the difference between the travel time under current traffic condition and the travel time under our congestion toll structure multiplied by the traffic volume per lane and value of time.

5.2 Volume

In terms of annual traffic volume, the new toll rate structure would result in an increase of annual traffic volume for FMT and JFK and a reduction for the rest of facilities. Our estimated tolls for BHT and FSK result in a reduction in the traffic volume across vehicle classes, except Class 10 for FSK and for the total at these two facilities (Table 3 (a)). Our estimated toll rates for WPL, TJH, and HWN are higher for Class 1-5 vehicles. Since these classes account for the majority of traffic (95%), a reduction in traffic volume in these classes override an increase in traffic volume in the rest of vehicle classes. In contrast, the reduction in traffic volume for Class 5-9 due to the new higher toll rates for FMT and JFK does not lead to a reduction of the total traffic volume.

Congestion tolls for WPL and BHT effectively reduce traffic volume during rush hours. The lower traffic volume results in an increase in traffic speed and shorter travel time, and produces social cost savings from preventing travel delay (Table 3 (d)). Among the three toll facilities, BHT has the most substantial improvements due to its length and per lane traffic volume: a reduction in traffic volume by 32 vehicles per hour, travel time saved by 9.4 seconds per vehicle, and the total delay cost savings of $130.26 per lane per hour. FMT's delay cost increase is due to a substantial increase in traffic volume resulting from very low optimal tolls in the first stage. Looking only at the effects of congestion tolls, FMT also shows positive effects as shown on the right side of Table 3 (d).

5.3 Revenue

Table 4 shows: (1) the revenue, traffic volume, emission, and ESAL under the current toll structure, (2) those under our estimated toll structure, and (3) the percentage change. Except for HWN and JFK, the other five facilities would see an increase in revenues. The dramatic increase of revenue at BHT is due to the rush-hour toll rates that contribute 72% of the total revenue. The contribution of congestion tolls to the total revenue is 49% and 34% for FMT and WPL respectively. As the current revenue for TJH is too low because of the AVI program, the estimated revenue would increase by 259% with the estimated tolls for TJH. For JFK, the decrease in the estimated tolls for Class 1-4 is not offset by the dramatic increase in the estimated toll rate for Class 5-9. Total revenue for the seven facilities would increase by 31% under our estimated toll rate structures.

Table 4 Revenue, Traffic Volume, Emission, Environmental Cost Savings, and ESAL

		Total	Facilities with Congestion		
			BHT (a)	FMT (b)	WPL (c)
Revenue	Current	$306,593,811	$37,271,658	$93,665,706	$37,053,023
	New Estimation	$401,921,820	$133,903,252	$108,736,763	$37,406,453
	% Change	31.09%	259.26%	16.09%	0.95%
Traffic Volume	Current	121,339,181	26,119,259	46,298,516	13,557,829
	New Estimation	121,130,112	26,045,486	46,415,371	13,542,303
	% Change	-0.17%	-0.28%	0.25%	-0.11%
Emission	Current	29,850,430,405	7,816,533,142	10,205,141,819	982,523,636
	New Estimation	29,857,420,158	7,794,925,701	10,226,029,718	981,403,297
	% Change	0.02%	-0.28%	0.20%	-0.11%
	Cost Savings ($)	$164,100	$109,498	-$4,040	$10,940
ESAL	Current	1,345,937	257,618	456,649	79,842
	New Estimation	1,344,395	257,044	456,306	79,834
	% Change	-0.11%	-0.22%	-0.08%	-0.01%
		Facilities without Congestion			
		FSK (a)	HWN (c)	JFK (b)	TJH (c)
Revenue	Current	$20,394,931	$10,039,944	$105,392,020	$2,776,529
	New Estimation	$20,650,889	$8,713,790	$82,544,283	$9,966,389
	% Change	1.26%	-13.21%	-21.68%	258.95%
Traffic Volume	Current	11,515,211	3,401,255	15,376,417	5,070,693
	New Estimation	11,492,907	3,400,625	15,419,828	4,813,592
	% Change	-0.19%	-0.02%	0.28%	-5.07%
Emission	Current	1,985,062,035	102,765,145	8,603,550,646	154,853,982
	New Estimation	1,981,130,377	102,764,066	8,623,409,539	147,757,461
	% Change	-0.20%	-0.001%	0.23%	-4.58%
	Cost Savings ($)	$22,333	-$922	-$16,527	$42,817
ESAL	Current	117,443	57,436	348,852	28,096
	New Estimation	117,123	57,707	348,530	27,850
	% Change	-0.27%	0.47%	-0.09%	-0.88%

Note: BHT has toll facilities at both directions. Revenues for these three facilities are for both directions. (a), (b), and (c) refer to categories of facilities listed in Table 4.

5.4 Emission and ESAL

Our estimated toll rates also result in a reduction of emissions for five facilities and a reduction in associated pollution costs for four facilities (Table 4). The emission level is calculated by multiplying emission rates from the HCA study (FHWA, 1997) with the traffic volume. Due to the lower estimated toll rates for Class 1-4, JFK and FMT has higher traffic volume, resulting in higher emission levels. For the other five facilities, lower estimated traffic volume leads to lower emission level.

Environmental cost savings (Table 4) from pollution reduction are calculated by finding the difference between the current emission level and estimated emission level and multiplying it by the marginal environmental cost estimated by McCubbin and Delucchi (1999). Lower estimated emission levels result in environmental cost savings from pollution reduction for BHT, WPL, FSK, and TJH. Higher estimated emission level for FMT and JFK leads to higher environmental costs. Overall, the new toll structure would achieve the total of $164,100 savings in environmental costs.

Another expected result from charging our estimated toll rates is a reduction in ESALs (Table 4), which would result in less road damage at the facilities. Even though the total traffic volume would increase for FMT and JFK, the total ESAL would still decrease since the increasing traffic volume is mainly for lower vehicle classes (Class 1-5) which have lower corresponding LEF. Lower traffic volumes result in lower ESAL for BHT, WPL, FSK, and TJH. For HWN, the effect of substantially lower estimated toll rates for Class 6-13 with higher LEF offset the effect of higher toll rates for Class 1-5 to result in reduction in toll revenue as well as an increase in ESAL. Overall, the new toll structure would achieve the total of 0.11% reduction in ESAL.

6. SENSITIVITY ANALYSIS

In the analysis in the previous section, we used a set of values for an interest rate, maintenance interval, and price elasticity of vehicle traffic that are considered reasonable. We conducted a series of sensitivity analysis to test how varying values of these factors affect analytical results.

Interest Rate: Two other values of interest rate—0.03 and 0.09—were tested to see how results change. The estimated toll rates tend to increase when the interest rate is raised from 0.03 to 0.06 and to 0.09 for the three bridges (WPL, HWN, and TJH) due to an increase in the infrastructure maintenance costs, construction costs and other capital costs that are sensitive to an interest rate. The toll rates did not change much for the other four facilities for: (1) the relatively low infrastructure costs for tunnels and (2) the relatively short distance of a bridge section within the entire facility.

In general, the magnitude of increase in toll rates due to higher interest rates was largest for Class 1-4 vehicles, the second largest for Class 10 and above, and the smallest for Class 5-9 vehicles. This is because of the combination of the general cost increase for all vehicles classes, a substantial increase in the maintenance costs based on their higher LEF values for Class 10 and above, and the high environmental costs applied to vehicles in Class 5 and above, which offsets the cost increase due to a higher interest rate.

In general, the higher interest rate also leads to more toll revenue, lower traffic volume, lower emissions, and lower ESAL for most of the facilities as shown in a change in percentage compared to the current conditions. Table 5 (a) shows results for the five facilities and confirms the previous results, except WPL with the interest rate of 0.03. This exceptional case with WPL results from a decrease in traffic volume of Class 1-5 vehicles that have lower LEF values and an increase in traffic volume of Class 6-10 vehicles that have higher LEF values. WPL’s congestion tolls are relatively small, while its toll increase in the first stage is also limited (Table 5 (b)). It should be noted that TJH’s higher revenue is due to a substantial discount currently provided for Classes 1-5 vehicles. Although this discount certainly benefits these regular users, it makes the financing of this facility far from a user fee concept. BHT’s large revenue increase is mainly due to the congestion tolls (Table 5 (b)). Focusing on the effect in peak hours for BHT, FMT and WPL, the higher the interest rate, the more reduction in rush-hour traffic, the higher speed, the more travel time saving, and the less delay cost (Table 5 (c)). However, because the toll rates in the first stage become so low for FMT that the total tolls with the congestion toll are still lower than the current toll rates, FMT would have higher rush-hour traffic volume.

Table 5 The Effects of Different Interest Rates on Revenue, Volume, Emission andESAL

(a) Changes in Revenue, Volume, Emission and ESAL	Interest Rate	Total	Facilities with Congestion			w/o Congestion	
			BHT	FMT	WPL	JFK	TJH
Revenue	0.03	20.20%	250.86%	11.41%	-31.04%	-25.15%	106.20%
	0.06	31.09%	259.26%	16.09%	0.95%	-21.68%	258.95%
	0.09	41.93%	267.63%	20.78%	32.61%	-18.22%	411.44%
Traffic Volume	0.03	0.14%	-0.23%	0.31%	0.78%	0.34%	-2.25%
	0.06	-0.17%	-0.28%	0.25%	-0.23%	0.28%	-5.07%
	0.09	-0.48%	-0.33%	0.20%	-1.02%	0.23%	-7.91%
Emission	0.03	0.12%	-0.23%	0.26%	0.70%	0.28%	-2.04%
	0.06	0.02%	-0.28%	0.20%	-0.11%	0.23%	-4.58%
	0.09	-0.07%	-0.32%	0.15%	-0.94%	0.18%	-7.14%
ESAL	0.03	-0.07%	-0.22%	-0.07%	0.26%	-0.08%	-0.28%
	0.06	-0.11%	-0.22%	-0.08%	-0.01%	-0.09%	-0.88%
	0.09	-0.16%	-0.23%	-0.08%	-0.28%	-0.10%	-1.49%

(b) Toll Revenue in Off-peak and Peak Hours	Interest Rate		Facilities with Congestion		
			BHT	FMT	WPL
(Non-peak Hour Revenue) / (Current Revenue)	0.03		97.40%	56.34%	41.93%
	0.06		101.85%	59.03%	66.63%
	0.09		106.30%	61.73%	91.27%
(Peak-hour Revenue) / (Current Revenue)	0.03		253.46%	55.06%	27.03%
	0.06		257.41%	57.06%	34.32%
	0.09		261.33%	59.05%	41.33%
(Rush Hour Revenue) / (Total Estimated Revenue)	0.03		72.24%	49.43%	39.19%
	0.06		71.65%	49.15%	34.00%
	0.09		71.09%	48.89%	31.17%

(c) Effects in Peak Hours	Interest Rate		Facilities with Congestion		
			BHT	FMT	WPL
Hourly Rush-hour Traffic Change (# of vehicles)	0.03		-30.70	8.80	-0.72
	0.06		-31.81	6.30	-21.13
	0.09		-32.92	3.80	-44.02
Travel Speed Change (km/hour)	0.03		0.63	-0.03	0.01
	0.06		0.65	-0.02	0.45
	0.09		0.68	-0.01	0.93
Travel Time Savings (seconds)	0.03		9.05	-0.19	0.04
	0.06		9.38	-0.14	1.59
	0.09		9.72	-0.08	3.26
Delay Cost Savings ($/lane/hour)	0.03		125.64	-2.13	0.64
	0.06		130.26	-1.52	22.82
	0.09		134.88	-0.92	46.56

Maintenance Interval: Two other values of resurfacing interval—10 and 20 years—were tested. The shorter (longer) resurfacing interval increases (lowers) the maintenance cost, toll rates, and revenue, and lowers (increases) the emission and ESAL level. The magnitude of effects is generally more substantial for the bridges and for higher vehicle classes than their counterparts because of their association with higher maintenance costs. For example, WPL, which has the longest bridge among the seven facilities, has the largest difference in toll rates, while the difference is smaller for JFK, which has a very short portion of the whole facility as a bridge. The effects of different values of maintenance interval are relatively small on the total traffic volume, the rush-hour traffic, speed, travel time saved, and delay cost saved, as it affects mainly on higher vehicle classes which shares a small portion of total traffic.

Elasticity: Although elasticity does not directly influence social costs associated with the usage of facility, it influences how traffic volume changes when toll rates change, and therefore revenue, vehicle emission, and ESAL. Three different sets of price elasticity for passenger cars and trucks—[-0.05, -0.05]; [-0.1, -0.01] and [-0.1, -0.05] in addition to the default values—to examine the effects of elasticity. The overall change in traffic volume depends on the composition of vehicle classes and on which tolls are higher, either current tolls or estimated tolls. In addition, the magnitude of effect is larger for elasticity of passenger cars than for trucks as the former makes up the majority of the traffic and have a larger impact on the total traffic volume. The traffic volume for BHT, WPL, and TJH shows a larger reduction with the lower value of elasticity. In contrast, the change in elasticity for passenger cars from -0.05 to -0.1 results in a larger increase in traffic volume since FMT and JFK have the estimated tolls that are lower than the current tolls for passenger cars. In addition, lowering the elasticity for trucks from -0.01 to -0.05 leads to a smaller increase in the total traffic volume since the estimated toll rates for vehicles in Class 5-9 and Class 11-12 are higher than the current toll rates. The general trends for emissions are similar to traffic volume. And the effects on toll revenues and ESAL are generally expected, following the patterns in the case of default values.

7. CONCLUSION

This study incorporates the social costs of driving by vehicle class into road pricing models in order to estimate socially optimal toll rates at two equilibrium points, taking into account feedback effects. The resulting change to traffic volume, toll revenue, vehicle emissions, and the total number of ESALs are compared to the tolls currently charged.

The analysis results showed substantial variation in the difference between the estimated tolls and the current tolls by vehicle class and among the toll facilities. The latter depends on a type of facility (either tunnel or bridge), the length of a highway portion of a facility relative to a tunnel or bridge portion, percentage of vehicle class, road functional class, and the level of congestion. Part of the current tolls based on the number of axles encourages the usage of vehicles with fewer axles but more weight among trucks and trailers, including Class 5-9 and 11-12 vehicles, for which the current tolls are too low to cover their responsible costs. This indicates that types of vehicle should be carefully taken into account as the effect of LEF overrides the effect of the number of axles. However, to our surprise, these expected results were not consistent for all facilities as the current tolls are set differently for different facilities. For example, the current toll rates should be increased for lower vehicle classes (Class 1 through 5) and decreased for higher vehicle classes for three facilities.

As expected, the three facilities with a clear sign of traffic congestion in peak periods could benefit in a reduction of traffic and travel time delay by imposing congestion tolls. Annual traffic volume would decrease for the five facilities as expected. At the same time, traffic would increase for two facilities because the current tolls are unexpectedly higher than the estimated tolls for lower vehicle classes and a reduction in tolls for induces a large increase in traffic of these vehicle classes. The aggregated toll revenue for the seven facilities would increase by 30 percent, while two facilities would have a reduction in revenue. Charging the estimated toll rates would also result in a reduction of emissions for five facilities and a combined annual savings of $164,100 for the seven facilities. Results from the sensitivity analysis generally support our main results with the default values.

To some degree, our analysis revealed the difficulty to obtain expected results from tolls based on social costs of driving as the relative magnitude of each cost factor as well as the current toll structure influences the effects of non-congestion costs in off-peak periods. A lack of clear pattern in the current toll structure among the facilities in relation to vehicle classes, combined with the analysis results in this study, indicates possible cross-subsidies among facilities as well as among vehicle classes. From both efficiency and equity points of view, it would be desirable to have a clear standard for factors to determine toll rates based on social costs of the usage of road infrastructure, rather than focusing on a cost recovery mainly for a responsible agency.

More research is warranted to examine a road pricing scheme that internalizes social costs of driving different types of vehicle. Such research will require more up-to-date relevant data. Despite a substantial amount of time spent to identify the best data by vehicle class available, some of the data used in this study—the 1997 FHWA HCAS data and truck emission data prior to the EPA engine standards beginning in 2000—are considered old. More accurate estimates of road damage costs would change the distribution of costs among vehicle types, as well as the overall maintenance costs. Larger variation of vehicle emission costs by vehicle type would probably have larger impacts on analysis results as these costs share relatively the higher proportion in the optimal tolls than other costs (except congestion costs) for most vehicle classes. Future research will require other works to increase the certainty in the valuation of social costs associated with driving by vehicle class, more efforts and coordination among different divisions in transportation agencies to collect data on facility construction and maintenance costs, traffic volume by vehicle type in a finer geographic level, and price-elasticity of traffic by vehicle type, and more integration of research among different subjects in the transportation study, such as traffic operation, pavement and structure, and economics and finance.

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