A Review and Advance of High-Occupancy Toll Lanes' Toll Schemes

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Abstract: This paper reviews the pricing of high-occupancy toll (HOT) lanes and finds that 1) existing dynamic pricing adjusts every 3-15 minutes according to such parameters as speed, density, and/or volume, 2) tolls increase progressively with traffic to ensure free flow HOT lanes, 3) for multi-zone HOT lanes, tolls tend to be determined by the most congested zone, 4) the reaction of motorists to toll adjustments is either unspecified or oversimplified, and 5) a toll boundary is essential to mediate extreme fluctuations. Based on values of time savings and reliability, a novel toll scheme was proposed as a function of speed of general-purpose lanes; tolls in a selected 10-mile HOT corridor varied between $0.77 and $12.64 per use, of which the value of reliability accounted for 24% to 44% while that of time savings accounted for the remainder. The proposed toll scheme can be applied to time-of-day or dynamic HOT pricing.

Keywords: High-Occupancy Toll, Congestion Pricing, Value of Time, Value of Reliability

1. INTRODUCTION

Capable of managing demand and generating revenue, high-occupancy toll (HOT) lanes are regarded as an improved alternative to high-occupancy vehicle (HOV) lanes. HOT lanes allow free or discounted tolls for HOVs while charging single-occupancy vehicles full rates. HOT lanes are designed to provide congestion-free services, maintain financial viability of the lanes, utilize available HOV capacity, preserve bus operating speeds and transit funding, and enhance safety and operations via increased flexibility (FHWA, 2004; OCTA, 2003). Implementations of HOT arose from two projects, the SR-91 Express Lanes (Orange County) and I-15 Express Lanes (San Diego), in southern California during mid 1990s. 11 corridors in the United States have implemented HOT lanes and another five are being planned or are under construction. A growing body of evidence shows that effective highway management through HOT is achievable and sustainable (FHWA, 2007).

The principle of HOT is straightforward: when general-purpose (GP) lanes are congested and unpredictable, the adjacent HOT lanes with light traffic become appealing to the motorists who are willing to pay a toll for mobility and reliability. The tolls increase with GP-lane traffic to maintain the HOT lane at free flow speed and match the rising willingness to pay. However, it is difficult to quantitatively realize an optimal HOT lane owing to theoretical deficiencies of toll schemes (Zhang et al., 2008; Lou et al., 2011). The introductory period for most HOT facilities could be from as short as months to as long as years in order to determine a proper toll structure (FHWA, 2011). Among the different toll patterns, time-of-day and static tolls do not reflect real-time traffic conditions, especially when traffic incidents lead to non-recurring congestion. Dynamic pricing is capable of dealing with non-recurring congestion, but does not necessarily ensure congestion free and well utilized HOT lanes (Liu et al., 2010). Some tolling structures have been constructed by simulation or travelers' surveys (see Zhang et al., 2008; Burris et al., 2009; Lou et al., 2011). These tolling structures depend upon various predetermined (or assumed) location-specific model parameters that are difficult to validate in the planning and operational stages.

Via an in-depth review of the HOT practice, the objective of this research is to build a traffic responsive toll scheme for HOT planners, operators, and decision makers. The proposed toll scheme incorporates two of the most frequently mentioned HOT incentives—travel time savings and reliability. As Taiwan is launching its first HOV lane in February 2013, the dynamic HOT pricing attribute could be potential advancement of Taiwan's freeway traffic management in the future. This paper is organized on the sequence of analyzing state-of-the-practice HOT tolling algorithms, developing a time saving- and reliability-based toll scheme, model implementation, discussion and conclusions.

2. STATE OF THE PRACTICE

2.1 Toll collections and rate patterns

The HOT lanes in operation can be divided into three rate patterns (flat, time-of-day, and dynamic rates) and three toll collections (pass-, per use-, and distance-based), as summarized in Table 1 and detailed in Table 2. Flat rates with pass-based toll collection are the simplest HOT toll scheme. Variable rates include time-of-day tolls and dynamic tolls. Time-of-day tolls are responsive to historical traffic variations and meanwhile stable for a long period, usually one h. Time-of-day tolls have been using since the SR-91 HOT opened, regardless of technical capacity for dynamic tolls available in late 1990s. Nowadays, distance-based dynamic pricing that reflects real-time traffic and fulfills the pay-as-you-use equity is becoming more popular. The toll system calculates a real-time rate based on traffic data from the on-site device. Distance-based toll collection either charges distance-related rates (such as the I-15 in San Diego and I-85 in Atlanta) or divides the HOT corridor into multiple per use-based toll zones or sections to provide ingress/egress between the HOT and main lanes (such as the I-394/I-35W in Minneapolis, I-10W in Houston, and I-15 in Salt Lake City).

Table 1. Toll collection and rate patterns of the exsiting HOT facilities

Toll Collection	Static:	Variable:	
	Flat Rate	Time-of-day Rate	Dynamic Rate
Pass-based	I-15, Salt Lake City, UT* (by 2010)	N.A.	
Per use-based	US-290, Houston, TX (Under rebuilding)	SR-91, Orange County, CA I-25, Denver, CO	I-15 South, San Diego, CA** I-95 Miami, FL SR-167, Seattle, WA I-680, Alameda County, CA
Distance/zone/section-based	N.A.	I-10W, Houston, TX	I-15 North, San Diego, CA** I-394/I-35W, Minneapolis, MN I-15, Salt Lake City, UT* I-85, Atlanta, GA

Note: * The I-15 HOT lanes in Salt Lake City origianlly operated with monthly pass in decal, and have transitioned to an electronic payment system that adopts zone-based dynamic toll rates since 2010.
** The I-15 South HOT lanes in San Diego have transitioned to charge distance-based tolls like the North.

2.2 Tolling algorithms

Five algorithms are reviewed as a reference for the proposed toll scheme. Elements in a tolling algorithm typically respond to the following questions:

1) How frequent is the toll adjustment made?
2) What is the basis (volume, density, speed, etc.) of the adjustment?
3) What is the period in which the basis is measured?
4) What is the increment and decrement of each adjustment?
5) What are the maximal increment and decrement, if any, of each adjustment?
6) What are the upper and low bounds, if any, of the tolls?
7) Specific needs for the considered case.

Table 2. Overview of the existing HOT facilities in the U.S.A.

Location	HOT Configuration (lanes in two directions)	Toll Policy	Toll Pattern and Range	Note	Administrator
I-15 (by 2010) Salt Lake City UT *	45.6-mi 2 lanes with intermediate access. 8 GP lanes.	HOV2+: free SOV: tolled	Monthly pass. $50 per month.	The longest HOT in the U.S.	UT DOT
US-290 Houston TX (before rebuilding)	14-mi reversible 1 lane w/o intermediate access. 8 GP lanes.	Peak (HOT lane) HOV3+: free HOV2: tolled SOV: prohibited Off peak (HOV2+lane)	A flat rate. $2 per use.	Now under rebuilding.	Metropolitan Transit Authority of Harris County
SR-91 Orange County CA	10-mi 4 lanes w/o intermediate access. 8 GP lanes.	Peak HOV3+: 50% toll off HOV2, SOV: fully tolled Off peak HOV3+: free HOV2, SOV: fully tolled	Time-of-day tolls. $1.3 ~ 10.05 per use.	The first HOT. Operation since 1995.	Orange County Transportation Authority
I-25 Denver CO	6.6-mi reversible 2 lanes w/o intermediate access. 8 GP lanes.	HOV2+: free SOV: tolled	Time-of-day tolls. $0.5 ~ 3.5 per use.	Tolls on SOV are not less than the express bus fare on the HOT.	CO DOT
I-10 W Houston TX	12-mi 4 lanes with intermediate access. 3 toll zones. 10 GP lanes.	Bus: free HOV2+: peak free; off-peak tolled SOV: tolled	Time-of-day tolls by zone. $0.3 ~ 1.6 per zone.	Newly widened. Original operation like US-290 in Houston.	Harris County Toll Road Authority
I-15 South (of SR-56) San Diego CA	8-mi reversible 2 lanes w/o intermediate access. 10 GP lanes.	HOV2+: free SOV: tolled	Dynamic tolls in a different tolling algorithm from the north section. $0.5 ~ 8 per use.	The first case (1996) of HOV converting to HOT. It has changed to the way I-15 North operates.	San Diego Association of Governments
I-95 Miami FL **	7.75-mi 4 lanes w/o intermediate access. 8 GP lanes.	HOV3+: free (registration required) HOV2, SOV: tolled	Dynamic tolls. $0.25 ~ 7.25 per use.	The first case in the east coast. Completion in three stages (2008/2010/2012).	FL DOT*
SR-167 Seattle WA	9-mi 2 lanes with intermediate access. 4 GP lanes.	HOV2+: free SOV: tolled	Dynamic tolls. $0.5 ~ 9 per use.	Implemented in 2008.	WS DOT
I-680 Alameda County, CA	14-mi 1 southbound lane with intermediate access. 3~4 GP lanes.	HOV2+: free SOV: tolled	Dynamic tolls. $0.3 ~ 1.75 per use.	Implemented in 2010.	I-680 Express Lane Joint Powers Authority
I-15 North (of SR-56) San Diego, CA	12-mi reversible 4 lanes with intermediate access. 8 GP lanes.	HOV2+: free SOV: tolled	Dynamic tolls by distance. $0.5 ~ 8 per use.	Implemented in 2011.	San Diego Association of Governments
I-394 Minneapolis MN	7-mi 2 lanes and 3.3-mi reversible 2 lanes with intermediate access. 5 toll zones and 2 sections. 4 GP lanes.	HOV2+: free SOV: tolled	Dynamic tolls by section. $0.25 ~ 8 per section.	The first dynamic and toll-by-section HOT. Implemented in 2005.	MN DOT
I-15 Salt Lake City UT *	40-mi 2 lanes with intermediate access. 4 toll zones. 8 GP lanes.	HOV2+: free SOV: tolled	Dynamic tolls by zone. $0.25 ~ 1 per zone.	Implemented in 2010. 12-mi SB expansion will be open in 2012.	UT DOT
I-85 Atlanta GA	15.5-mi 2 lanes with intermediate access. 10 GP lanes	HOV3+: free SOV, HOV2: tolled	Dynamic tolls by distance. $0.1~0.9 per mile.	Implemented in 2011.	GA DOT

Source: compiled from the HOT websites (see the references). Note: * See the first note in Table 1. ** The additional 10 miles of Florida I-91 HOT Phase 2 are under construction and will have multi-entry/exit points and -toll zones.

2.2.1 SR-91, Orange County, California

The current SR-91 toll schedule (effective from January 1, 2013) has a maximum of $9.55 per use, about $1 per mile that tops other HOT facilities in the country. The schedule is seasonally renewed on the first day of January, April, June, and October. The tolls are determined by the following criteria (OCTA, 2003):

$$\begin{cases} Q_{kt} > 1{,}650 & \Rightarrow\ Toll_{k,t+1} = Toll_{kt} + 1.00\,;\, Toll_{k,t+2} = Toll_{k,t+1} \\ 1{,}650 > Q_{kt} > 1{,}600 & \Rightarrow\ Toll_{k,t+1} = Toll_{kt} + 0.75\,;\, Toll_{k,t+2} = Toll_{k,t+1} \\ 1{,}600 > Q_{kt} > 1{,}360 & \Rightarrow\ Toll_{k,t+1} = Toll_{kt} \\ 1{,}360 > Q_{kt} & \Rightarrow\ Toll_{k,t+1} = Toll_{kt} - 0.50 \end{cases} \tag{1}$$

where,

Q_{kt} : the directional average volume (veh/h/ln or vphpl) at hour k on the day of week in period t that includes the last 12 consecutive weeks but excludes holidays and hours with major incidents and accidents, and

$Toll_{kt}$: the time-of-day toll rate ($/use).

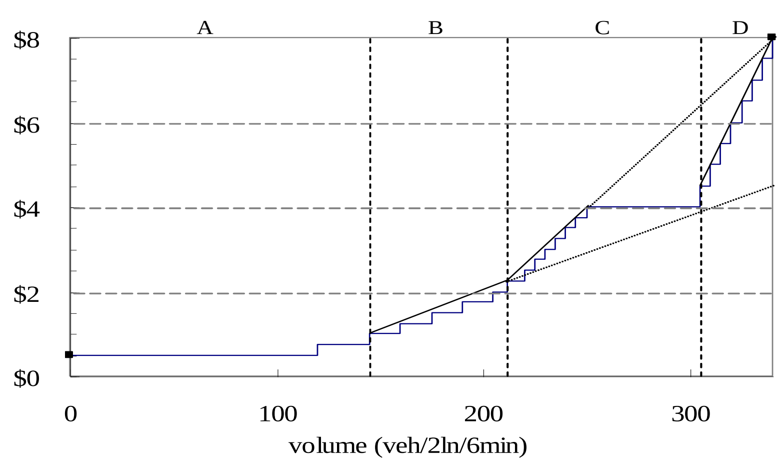
The first two criteria freeze tolls in the next period if the current ones have just increased. Such a mechanism prevents continuous toll rises and ensures a relatively stable toll schedule. Not listed above, the toll scheme also considers such factors as an annual adjustment for inflation and the majority of the volumes in the 12-week period in addition to the averages. Time-of-day rates have the advantage that motorists can respond to the toll schedule or adjust their travel plans in advance, but the drawback is not real-time traffic responsive.

2.2.2 I-15 South (of SR-56), San Diego, California

Although I-15 South HOT pricing has converted to the way I-15 North operates, its original design is classic and worth reviewing. Renewed every 6 min, the toll rates are determined by the latest 12-min volume of the two-lane HOT given a volume-toll lookup table as Table 3. The goal of the toll scheme is to keep the HOT no worse than volume-based level of service (LOS) C. Each toll adjustment follows the lookup table but is within a maximal increase of $1 for traffic conditions at or above LOS C, or $0.5 otherwise (SANDAG, 2006). There are 23 toll rates from LOS A through D. Tolls at LOS A mainly stay at $0.5 and raise $0.25 at LOS B for every 15-vehicle increase in 6 min on the HOT lanes. Tolls at LOS C are two-phased, raising $0.25 at the first for a 5-vehicle increase but freezing at the second. Tolls at LOS D have the sharpest rise of $0.5 for a 5-vehicle increase. Although heavy HOT traffic corresponds to a higher toll increment, the design of maximal allowable increase prevents a huge toll rise at once.

Table 3. HOT volume-toll lookup table

	12-min Volume Lower Thesholds	Equivalent 6-min Average Volume	Level Of Service (LOS)	Maximal Rate Per Theshold
1.	< 240	< 120	A	$0.50
2.	240	120	A	$0.75
3.	290	145	B	$1.00
4.	320	160	B	$1.25
5.	350	175	B	$1.50
6.	380	190	B	$1.75
7.	410	205	B	$2.00
8.	425	212	C	$2.25
9.	440	220	C	$2.50
10.	450	225	C	$2.75
11.	460	230	C	$3.00
12.	470	235	C	$3.25
13.	480	240	C	$3.50
14.	490	245	C	$3.75
15.	500	250	C	$4.00
16.	610	305	D	$4.50
17.	620	310	D	$5.00
18.	630	315	D	$5.50
19.	640	320	D	$6.00
20.	650	325	D	$6.50
21.	660	330	D	$7.00
22.	670	335	D	$7.50
23.	680	340	D	$8.00



Note: Volumes are in two lanes. Table is from SANDAG (2006), on which the diagram is based.

2.2.3 I-15 North (of SR-56), San Diego, California

Distinct from the I-15 South HOT that was originally accessible only at the end points, the I-15 North has entries and exits along the HOT corridor. In recognition that a single dynamic toll rate do not meet the need of various tolls at different ingress/egress points, SANDAG (2006) proposed a dynamic tolling algorithm that reflects HOT traffic conditions and HOT time savings over GP lanes. The HOT corridor is divided into *n* zones with tolls derived from the following steps (see Table 4 for example):

1) Settings of initial parameters.
   a. Minimal acceptable average HOT speed: 60 mph.
   b. Value of time: $0.4/min. It is also a minimum and starting value of time.
   c. Maximal Value of time: $0.8/min.
   d. Value of time increment/decrement: $0.08/min.
   e. Minimal rate: $0.1/mi (peak), $0.05/mi (off-peak).
   f. Maximal rate: $1/mi.
2) Determine the value of time for zone *i* at time period *t*.
   a. If the average speed in each downstream zone (i = m to n) falls above the minimal acceptable average speed for two consecutive periods t-1 and t-2, the value of time for each downstream zone at period t decreases by $0.08/min.
   b. If the average speed in any downstream zone *k* falls below the minimal acceptable average speed for two consecutive periods, the value of time for zone *k* and its upstream zones at period *t* increase by $0.08/min.
   c. Otherwise the value of time remains the same.
3) The toll rate for zone *i* at time *t* is the monetary value of the downstream cumulated time savings divided by the total downstream length.
4) The lower and upper bounds for the value of time and toll rates are set to prevent extreme pricing on the HOT facilities.

With the unit of dollars per mile, I-15 North can accurately charge users according to the HOT distance they travel. Step 2 sets a lower bar for increasing the value of time, which ensures HOT at free flow speed but possibly causes underutilization in some toll zones. The algorithm simplifies tolls to be solely related to travel time savings, albeit studies (Lam and Small, 2001; Brownstone et al., 2003; Liu et al., 2004; Small et al., 2005) have shown that travel reliability plays a substantial role. Such simplification is also found in previous studies (Zhang et al., 2008; Lou et al., 2011) that applied travel times on the HOT and GP lanes to reversely simulate tolls.

Table 4. Conversion from travel time savings to toll rates

Zone ID	M	m+1	→	N
Zone length (mi)	L_m	L_{m+1}	…	L_n
Speed at period *t*-1 (mph)	$S_{GPm,t-1}, S_{HOTm,t-1}$	$S_{GPm+1,t-1}, S_{HOTm+1,t-1}$	…	$S_{GPn,t-1}, S_{HOTn,t-1}$
Cumulative time savings *CTS* at period *t*-1 (min)	$\sum_{i=m}^{n} 60\left(\frac{L_i}{S_{GPi,t-1}} - \frac{L_i}{S_{HOTi,t-1}}\right)$	$\sum_{i=m+1}^{n} 60\left(\frac{L_i}{S_{GPi,t-1}} - \frac{L_i}{S_{HOTi,t-1}}\right)$	…	$60\left(\frac{L_n}{S_{GPn,t-1}} - \frac{L_n}{S_{HOTn,t-1}}\right)$
VOT at period *t* (\$/min). See Step 2	$VOT_{m,t}$	$VOT_{m+1,t}$	…	$VOT_{n,t}$
Monetary value of *CTS* at period *t* (\$)	$CTS_{m,t-1} \cdot VOT_{m,t}$	$CTS_{m+1,t-1} \cdot VOT_{m+1,t}$	…	$CTS_{n,t-1} \cdot VOT_{n,t}$
Toll rate at period *t* (\$/mi)	$\frac{CTS_{m,t-1} \cdot VOT_{m,t}}{\sum_{i=m}^{n} L_i}$	$\frac{CTS_{m+1,t-1} \cdot VOT_{m+1,t}}{\sum_{i=m+1}^{n} L_i}$	…	$\frac{CTS_{n,t-1} \cdot VOT_{n,t}}{L_n}$

2.2.4 I-394, Minneapolis, Minnesota

The 10.3-mile I-394 HOT lane renews tolls every 3 min based on the latest 6-min density and a lookup table. It has five toll zones and two toll sections. Single occupancy vehicles on the HOT lane would be charged once within one toll section. I-394 is the first dynamic-pricing HOT lane with multiple ingress/egress points. Based on the algorithm, the most congested downstream toll zone decides the toll rates. Traffic on the GP lanes is not directly weighed but relatively reflected by the changing density on the HOT lane. Four steps determine the rate of a toll zone, as shown below. Robbins et al. (2009) reported a similar approach adopted on the I-95 HOT lane in Miami, Florida, despite tolls updating every 15 min.

1) Calculate individual 30-sec density (veh/ln/mi) from each detector along the HOT lane.
2) The 30-sec calculations are averaged by zone over the latest 6-min period for every 3 min.
3) Density in zone *i* at period *t*, $D_{i,t}$, is set as the maximal 6-min density downstream. Delta density at *t* is $D_{i,t}$ minus $D_{i,t-1}$.
4) Use the delta density-toll increment lookup table (Table 5) to find the net increase or decease of the toll. The toll at period (*t*+1) is that at t plus the net value from the lookup table.

Table 5. Extract of delta density-toll increment lookup table

LOS	**Density**
A	0–11
B	>11–18
C	>18–29
D	>29–35
E	>35–45
F	>45

$D_{i,t}$ \ $D_{i,t}-D_{i,t-1}$	=1	=2	=3	=4	=5	=6
20	\$0.00	\$0.25	\$0.50	\$0.75	\$1.00	\$1.25
21	\$0.00	\$0.25	\$0.50	\$0.75	\$1.00	\$1.25
22	\$0.00	\$0.25	\$0.50	\$0.75	\$1.00	\$1.25
23	\$0.00	\$0.25	\$0.50	\$0.75	\$1.00	\$1.25
24	\$0.00	\$0.25	\$0.50	\$0.75	\$1.00	\$1.25
25	\$0.00	\$0.25	\$0.50	\$0.75	\$1.00	\$1.25
26	\$0.00	\$0.25	\$0.50	\$0.75	\$1.00	\$1.25
27	\$0.00	\$0.25	\$0.50	\$0.75	\$1.00	\$1.25
28	\$0.00	\$0.25	\$0.50	\$0.75	\$1.00	\$1.25
29	\$0.00	\$0.25	\$0.50	\$0.75	\$1.00	\$1.25

Note: Net values become negative if ($D_{i,t}-D_{i,t-1}$) is negative.

2.2.5 SR-167, Seattle, Washington

Tolls for the SR-167 HOT in Seattle renew every 5 min based on the equations below. More complex than above-mentioned algorithms, the SR-167 HOT considers speed and volume of both lane types as well as other predetermined parameters.

$$Toll_t = Toll_{t-1} + T_{inc} \cdot Round\left(\left(W_{hot} \cdot TIM_{hot} + W_{gp} \cdot TIM_{gp}\right) T_{scale}\right) \quad (2)$$

$$TIM_{hot} = W_{vcf} \cdot \left(\frac{V'_{hot}}{v_{scale\_hot}}\right) \cdot VWF_{hot} + W_{scf} \cdot \left(-S'_{hot}\right) \cdot SWF_{hot} \quad (2.1)$$

$$TIM_{gp} = W_{vcf} \cdot \left(\frac{V'_{gp}}{v_{scale\_gp}}\right) \cdot VWF_{gp} + W_{scf} \cdot \left(-S'_{gp}\right) \cdot SWF_{gp} \quad (2.2)$$

$$W_{hot} + W_{gp} = 1; \;\; W_{vcf} + W_{scf} = 1 \quad (2.3)$$

where,

$T_t\ (T_{t-1})$	: the toll at period *t* (*t*-1),
T_{inc}	: the toll increment with a default value of \$0.25,
$W_{hot}\ (W_{gp})$	: the weight of HOT (GP) lanes (0.9 and 0.1 by default),
$TIM_{hot}\ (TIM_{gp})$	: the toll increment measure,

T_{scale} : the toll increment scaling factor (1 by default),
$W_{vcf}\,(W_{scf})$: the weight of volume (speed) change factor (0.5 by default),
$V^{'}\ (S^{'})$: change in volume (speed) at the period with respect to HOT and GP lanes,
v_{scale} : the factor converting volume to speed, and
VWF (*SWF*) : the volume (speed) weighting factor for heavy traffic.

Substituting the default parameter settings to Eq. (2) reveals that the tolls mainly depend on the HOT lane speed and volume, as shown in Eq. (3). This complex toll adjustment equation, however, does not guarantee a more effective HOT lane (Liu et al., 2010).

$$Toll_t = Toll_{t-1} + 0.25 \cdot Round\begin{pmatrix} 0.45\left(\dfrac{V_{hot}^{'}}{v_{scale\_hot}} \cdot VWF_{hot} - S_{hot}^{'} \cdot SWF_{hot}\right) + \\ 0.05\left(\dfrac{V_{gp}^{'}}{v_{scale\_gp}} \cdot VWF_{gp} - S_{gp}^{'} \cdot SWF_{gp}\right) \end{pmatrix} \quad (3)$$

2.3 Summary

The tolling algorithms, as compared in Table 6, have the following similarities:

1) The algorithms commonly apply speed, density, and/or volume accessible to most traffic management centers.
2) When traffic becomes heavy, the algorithms generate progressively increasing tolls to more effectively manage the HOT lanes under a free flow state.
3) Dynamic tolls typically update every 3 to 15 min to cope with traffic variations. The impact of different update frequencies on traffic operations is unclear, albeit Sullivan (2000) reported the SR-91 HOT marketing analysis that some potential customers are uncomfortable with the unpredictability of dynamic tolls.
4) For multi-zone HOT lanes, toll rates tend to be determined by the most congested zone. A compromise behind is that such a design ensures free flow speed along the whole HOT corridor but may cause some zones in noticeable underutilization.
5) The reaction of motorists to toll adjustments is either unspecified or oversimplified in these algorithms.
6) A boundary can be set to maintain toll fluctuations within an acceptable range.
7) No evidence shows that a complex algorithm functions more effectively than a plain one.

Table 6. Comparison of the exemplified tolling algorithms

	SR-91, CA	I-15 South, CA	I-15 North, CA	I-394, MN	SR-167, WA
HOT total length (mi)	10	8	12	10.3	9
Toll update frequency	Season	6 min	6 min	3 min	5 min
Basis	(mean) HOT hourly volume	HOT volume	HOV and GP lane speed & VOT	HOT density	HOV and GP lane speed & volumes
Period of the basis	Latest 12 weeks	Latest 12 min	Latest 12 min	Latest 6 min	Latest 5 min
Reference	Four criteria for toll adjustments	A lookup table for toll adjustments	Three criteria for VOT adjustments	A lookup table for toll adjustments	An equation for toll adjustments
Increment ($)	1; 0.75	A multiple of 0.25	$0.08/min for VOT	A multiple of 0.25	A multiple of 0.25
Decrement ($)	0.5	A multiple of 0.25	$0.08/min for VOT	A multiple of 0.25	A multiple of 0.25
Max increment ($)	1	0.5 for LOS worse than C; otherwise 1	$0.08/min	N.A.	N.A.
Max decrement ($)	0.5	N.A.	$0.08/min	N.A	N.A
Upper bound	N.A.	$8/use	$1/mi	$8/section	$9/use
Lower bound	N.A.	$0.5/use	off-peak: $0.05/mi peak: $0.1/mi	$0.25/section	$0.5/use

Note: The tolls of SR-91 are not dynamic and thus do not have an upper or lower bound.

3. TIME SAVINGS- & RELIABILITY-BASED TOLLS

A complete tolling algorithm involves many elements. The core is how tolls respond to HOT and/or GP lane traffic. Tolls can be produced from either lookup tables (like Tables 3 and 5), equations (like Eq. (2)), or criteria (like Eq. (1) and Step 2 of I-15 North). However, little literature documents how these toll-traffic relationships were established. Studies (Lam and Small 2001; Ghosh 2001; Brownstone et al. 2003; Steimetz and Brownstone 2005; Small et al. 2005) have indicated that HOT users regard not only time savings but reliability as the determinants of choosing HOT lanes. These two determinants can be covered in the proposed toll scheme via adopting value of time (*VOT*) and value of reliability (*VOR*).

VOT and *VOR* have been typically derived from Logit-related models with data from stated preference (SP), revealed preference (RP), or both techniques. Brownstone and Small (2005) compiled *VOT* and *VOR* from various studies of the SR-91 and I-15 South HOT lanes. It was found the hourly median *VOT* between $9 and $16 if use of SP data while that between $20 and $45 (with majority within $20 to $30) and hourly median *VOR* of $20 if use of RP data. Instead of conducting SP or RP survey, Liu et al. (2004) adopted loop detector data and genetic algorithms to estimate *VOT* and *VOR*. It was found SR-91 motorists with hourly median *VOT* and *VOR* about $13 and $21, respectively. The I-15 North HOT project (SANDAG, 2006) employs a changing *VOT* with a minimum of \$24/h and a maximum of \$48/h. The SR-167 study (Zhang et al., 2008), on the other hand, employs a fixed *VOT* of \$11.7/h. In brief, previous research and empirical settings have presented general agreement on *VOR* but less consistency in *VOT*—values range from as low as \$9/h to as high as \$48/h. A single *VOR* of \$20/h and *VOT* of \$25/h and \$13/h are adopted for further analysis.

Speed is used for two reasons to connect time savings and travel reliability. First, there are existing cases (I-15 North and SR-167 HOT) applying speed-responsive tolls. Second, speed is perceivable by motorists and accessible to traffic management centers. Although additional traffic measures (like volume or density) can possibly construct a more comprehensive toll scheme, no evidence shows such addition helpful for more effective HOT operations. Empirical observations and the prior research (Liu et al., 2003; Small et al., 2005) have indicated that HOT lanes generally remain at free flow speed. Toll adjustments are therefore responsive to GP lane speed instead of HOT speed. The toll scheme is constructed as follows and shown in Figure 1:

1) Calculate HOT travel time savings TS_{hot} (h).

$$TS_{hot} = \frac{L}{S_{gp}} - \frac{L}{S_{hot}} \tag{4}$$

where L is the HOT length (mile); S_{gp} and S_{hot} are the mean speed (mph) of the GP lanes and HOT lanes. S_{hot} can be replaced by free flow speed (*ffs*).

2) Obtain the total value of HOT travel time savings *TVOT* (\$/use).

$$TVOT = TS_{hot} \cdot VOT = \left(\frac{1}{S_{gp}} - \frac{1}{ffs} \right) L \cdot VOT \tag{5}$$

where value of time has two scenarios of \$25 and \$13/h.

3) Capturing the notion that drivers are concerned mostly about unexpected delays in their commutes, travel time fluctuation is used to reflect travel reliability (Lam and Small, 2001; Brownstone et al., 2003; Liu et al., 2004; Small et al., 2005). Assume the HOT lanes are perfectly reliable, i.e., the HOT lanes operate uniformly at free flow speed and its reliability is associated only with GP lanes' travel time fluctuation. The assumption of zero HOT speed variance may not be practically true, but such small variations likely elude the users' perception. According to prior studies (Small et al., 2005; Liu et al., 2003), the HOT reliability is measured by travel time difference between the 80th and 50th percentile travel times on the GP lanes. The limitation of framing reliability in such a form is that motorists unlikely to capture accurate reliability. Rather, they probably rely on their perceived reliability (from daily commuting experiences).

$$\Delta TT_{gp} = TT_{gp}^{80\%ile} - TT_{gp}^{50\%ile} = \frac{L}{v_{gp}^{20\%ile}} - \frac{L}{v_{gp}^{50\%ile}} \tag{6}$$

where ΔTT_{gp} is the travel time fluctuation on the GP lanes (h); $TT_{gp}^{80\%ile}$ and $TT_{gp}^{50\%ile}$ are the 80th and 50th percentile travel times (h) respectively obtained via the 20th percentile speed $v_{gp}^{20\%ile}$ and 50th percentile speed $v_{gp}^{50\%ile}$ (mph).

4) Different distributions of speed v over a period of time have been found, such as bell shaped normal distribution (May, 1990; McShane and Roess, 1990) or positive skewed gamma or log normal distribution (Richardson et al., 1978; Nie et al., 2012). As an illustration, normal distribution is used and v on the GP lanes can be estimated via its mean speed S_{gp} and standard deviation SD_{gp} (mph). SD_{gp} can be obtained through field survey, simulation or a given relationship between S_{gp} and SD_{gp}.

$$\begin{cases} v_{gp}^{20\%ile} = S_{gp} - 0.84SD_{gp} \\ v_{gp}^{50\%ile} = S_{gp} \end{cases} \tag{7}$$

where the z value of -0.84 corresponds to the 20th percentile spot in the standard normal distribution. Substitution of Eq. (7) on Eq. (6) leads to Eq. (8).

$$\Delta TT_{gp} = \frac{L}{S_{gp} - 0.84SD_{gp}} - \frac{L}{S_{gp}} \tag{8}$$

5) Obtain the total value of HOT travel reliability $TVOR$ ($/use).

$$TVOR = \Delta TT_{gp} \cdot VOR = \left(\frac{1}{S_{gp} - 0.84SD_{gp}} - \frac{1}{S_{gp}} \right) L \cdot VOR \tag{9}$$

6) The HOT toll is defined as the total value of time savings and reliability.

$$Toll = TVOT + TVOR \tag{10}$$

$$= \left(\frac{1}{S_{gp}} - \frac{1}{ffs} \right) L \cdot VOT + \left(\frac{1}{S_{gp} - 0.84SD_{gp}} - \frac{1}{S_{gp}} \right) L \cdot VOR \quad \text{(\$/use) or} \tag{10.1}$$

$$toll = \left(\frac{1}{S_{gp}} - \frac{1}{ffs} \right) VOT + \left(\frac{1}{S_{gp} - 0.84SD_{gp}} - \frac{1}{S_{gp}} \right) VOR \quad \text{(\$/mi/use)} \tag{10.2}$$

7) If the goal of a free flow HOT lane is violated or the HOT lane is underutilized, the operator could adopt a more vigorous pricing approach to sustaining the goal.

$$Toll^{'} = m\left[\left(\frac{1}{S_{gp}} - \frac{1}{ffs} \right) L \cdot VOT + \left(\frac{1}{S_{gp} - 0.84SD_{gp}} - \frac{1}{S_{gp}} \right) L \cdot VOR \right] \quad \text{(\$/use)} \tag{11}$$

where m is a multiplier predetermined by the operator. $m > 1$ allows a quick response to HOT deterioration, $m = 1$ presents a normal tolling scheme that the HOT lane maintains at free flow speed, and $m < 1$ deals with HOT underutilization.

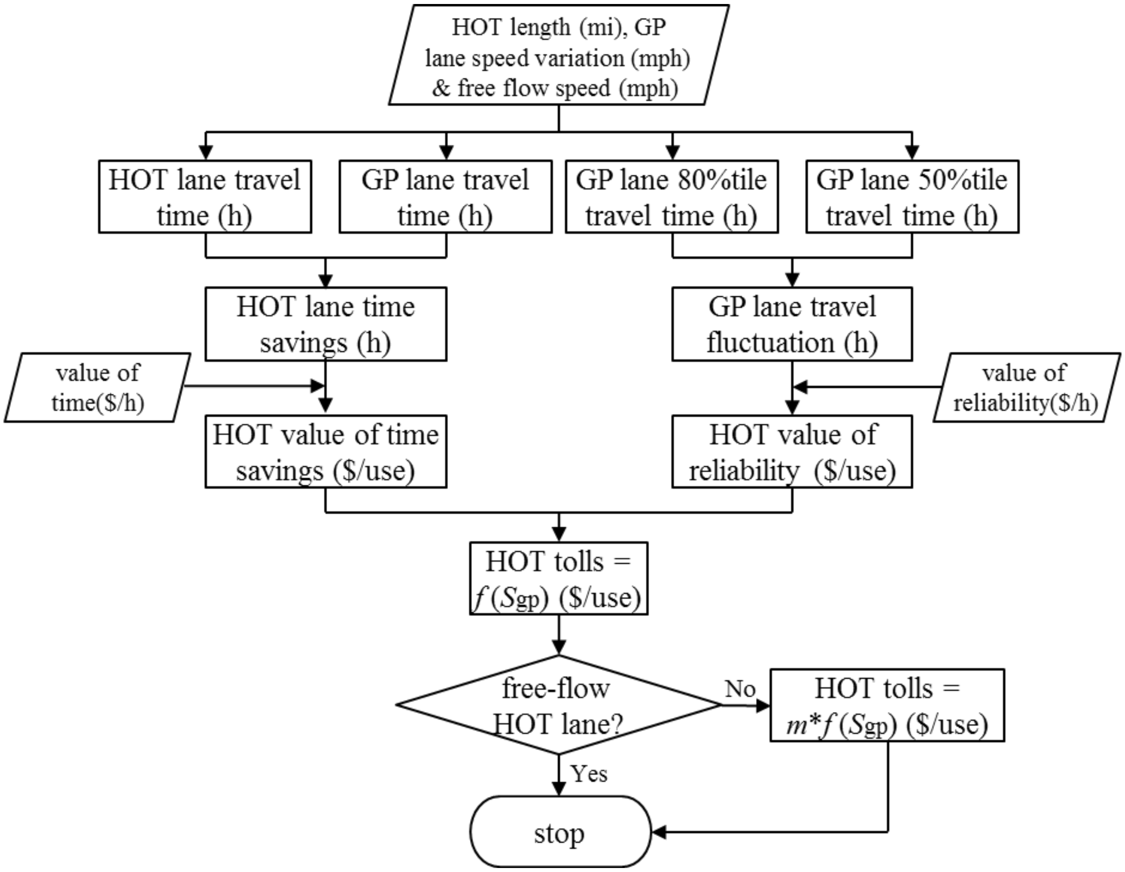


Figure 1. Flowchart of HOT toll assessment

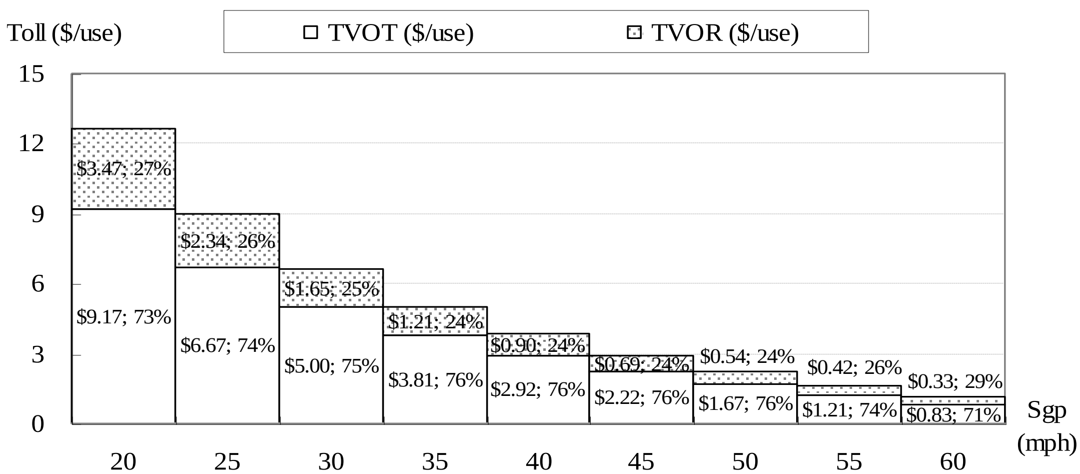
4. MODEL IMPLEMENTATION

4.1 Study site

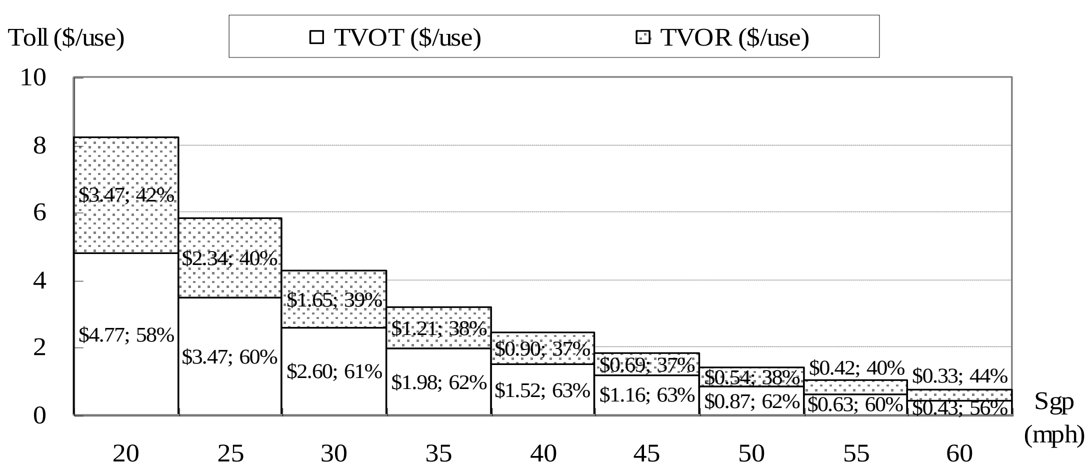
The study site is the SR-91, with directional two HOT lanes and four GP lanes in California, for its complete dataset that supports the model settings and validation. This 10-mile HOT corridor connects job centers in Orange County and residential areas in Riverside County ($L = 10$). The speed limit is 65 mph while the HOT lanes typically remain at free flow speed with moderate utilization ($ffs = 75$ and $m = 1$). Based upon the *VOT* and *VOR* studies compiled by Brownstone and Small (2005), two *VOT* scenarios of \$25/h and \$13/h are considered along with a single *VOR* of \$20/h. The relationship between standard deviation of speed and average speed of the GP lanes, $SD_{gp} = 51.6 S_{gp} Exp(-0.026 S_{gp})$, is built upon the field data. Substituting the above settings into Eq.(11) identifies the relationship between tolls and GP lane speeds.

4.2 Results

The proposed tolls under both *VOT* scenarios progressively increase with the GP lane traffic, ensuring greater responses to congestion. As shown in Figures 2(a) and 2(b), the value of travel reliability weighs differently across the speed bins. In Scenario 1 (*VOT*=$25/h, *VOR*=$20/h), the tolls vary from $1.17 to $12.64 per use as the GP lane speed drops from 60 to 20 mph. The value of travel reliability accounts for 24% to 29% and the value of time savings accounts for the remainder. In Scenario 2 (*VOT*=$13/h, *VOR*=$20/h), the tolls vary from $0.77 to $8.24. The value of travel reliability accounts for 37% to 44% because of a smaller *VOT*. Both scenarios show that the weights of the value of travel reliability are lower at GP lane speed between 40 and 50 mph, but higher at the two speed ends of 20 and 60 mph. Both scenarios in Figure 2 are approximated well by negative exponentially shaped curves as Eq. (12), upon which Table 7 can be built.



(a) Scenario 1: *VOT* = $25/h and *VOR* = $20/h



(b) Scenario 2: *VOT* = $13/h and *VOR* = $20/h

Figure 2. Speed-responsive tolls

Table 7. GP Lane Speed-Toll Lookup Table

GP lane speed (mph)	HOT toll rates ($/10mi/use)	
	Scenario 1	Scenario 2
>= 65	0.75	0.50
60 ~ 65	1.00	0.75
55 ~ 60	1.50	1.00
50 ~ 55	1.75	1.25
45 ~ 50	2.50	1.50
40 ~ 45	3.25	2.00
35 ~ 40	4.50	2.75
30 ~ 35	6.00	4.75
25 ~ 30	8.00	5.00
20 ~ 25	10.50	6.75
<= 20	12.25	7.75

$$Toll = \begin{cases} 39.005 Exp(-0.058 S_{gp}) \middle| VOT = 25; VOR = 20 \quad R^2 = 0.999 \\ 24.972 Exp(-0.058 S_{gp}) \middle| VOT = 13; VOR = 20 \quad R^2 = 0.999 \end{cases} \tag{12}$$

5. DISCUSSION

Figure 3 contrasts the empirical SR-91 tolls with the modeled toll-speed curves. A fundamental difference between these two is that the empirical tolls depend on historical HOT volumes while the modeled tolls depend on real-time HOT time savings and reliability over the GP lanes. Low GP lane speed may not empirically correspond to higher HOT tolls because 1) the historical data do not sufficiently reflect the real-time traffic, 2) the change in the HOT volumes does not match the change of the GP lane speed, and 3) the mechanism of frozen rates makes a second toll rise for a certain hour only possible after six months, causing the empirical tolls not so responsive to traffic variations.

As also shown in Figure 3, the empirical maximum ($9.55) is about in the middle of the modeled maximums of Scenarios 1 ($12.23) and 2 ($7.83), while the empirical minimum ($1.25) is closer to the modeled minimum of Scenario 1 ($1.20). Let toll dispersion be the mean absolute difference between the empirical and modeled tolls. For eastbound, Scenario 1 has greater toll dispersion of $3.40 than Scenario 2 of $2.90; for westbound, Scenario 1 has less toll dispersion of $2.12 than Scenario 2 of $2.37. Neither scenario is superior to the other. The toll rates can be converted to per mile-based if the HOT corridor is divided into several zones instead of one. Such toll-speed relationships as in Eq. (12) and Table 7 and combined with the key elements in Table 6 can facilitate constructing a complete tolling algorithm for time-of-day or dynamic pricing.

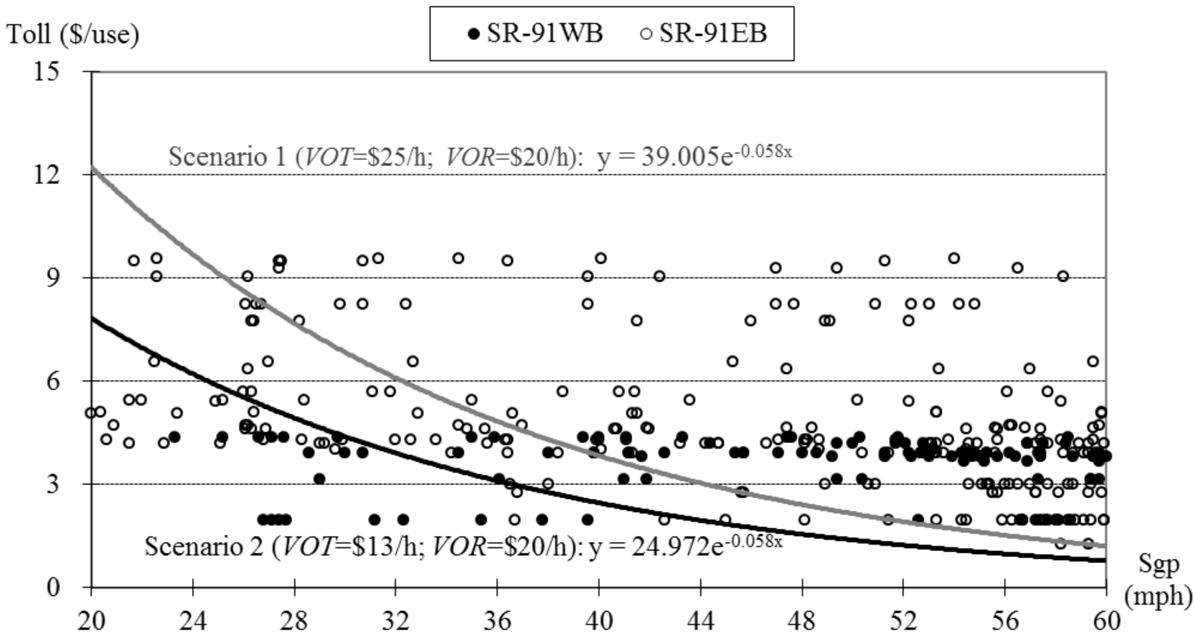


Figure 3. Proposed toll-speed diagrams vs. empirical data

Similar to the current toll schemes, this model applies only one parameter, GP lane speed, which is accessible to most traffic management centers. This model enables a higher toll increase rate when traffic becomes heavy, and is straightforward when compared to the existing SR-167 algorithm or others (Zhang et al., 2008; Burris et al., 2009; Lou et al., 2011) that require various predetermined parameters. The proposed scheme is comprehensive in reflecting both value of time and value of reliability that are unconsidered by the current practice.

Although the tolls correspond solely to GP lane speed, HOT traffic should be consistently monitored. The toll scheme breaks down when the free flow HOT condition is not sustained. The HOT lanes below free-flow speed result in less travel time savings and reliability, which lead to a lower toll. A lower toll introduces more vehicles from the GP lanes to the HOT lanes, thus worsening the situation. Congested HOT lanes violate the goal of HOT operations as well as the premise of this model. Approaches to avoid HOT congestion include 1) temporary closure of the HOT lanes to tolled vehicles, 2) adopting a higher toll level, such as Eq. (11) with *m* greater than 1, to mitigate demand, or 3) lifting the toll to its maximum. Conversely, if the HOT lanes are underutilized, adopting a lower toll level, such as Eq. (11) with *m* less than 1, to stimulate demand could help.

More and more agencies consider HOT as a mechanism to generate revenue as a result of shrinking budgets and growing congestion (FHWA, 2004). Nonetheless, the priority of HOT design should be given to demand management that maximizes congestion-free vehicles on HOT.

Demand management issues, including whether the toll scheme maximizes congestion-free vehicles, and the effect of tolls on transforming the paying vehicles into free or discounted vehicles, can be investigated in consecutive studies given the toll structures. Finally, as the tolls depend on the VOT and VOR, location-specific values should be assessed before applying the toll scheme. Also, VOT or VOR is essentially more about a distribution associated with factors like trip purposes (Liu et al., 2004; Patil et al., 2011), and stochastic HOT toll models could be potentially considered in the future.

6. CONCLUSIONS

The tolls of the HOT lanes in operation are decided via lookup tables (like Tables 3 and 5), equations (like Eq. (2)), or criteria (like Eq. (1) and Step 2 of I-15 North). Reviewing the existing HOT toll schemes brought following findings: the tolling algorithms commonly apply speed, density, and/or volume accessible to most traffic management centers, dynamic tolls increase progressively with traffic and update every 3 to 15 min to reflect traffic variations, tolls for multi-zone HOTs are determined by the most congested zone, the reaction of motorists to toll adjustments is unspecified, and toll boundaries are set to mediate extreme fluctuations.

HOT tolls were commonly used to assess VOT and VOR in many prior studies. Reversely, this research assessed HOT tolls based on both values with GP lane speed as an intermediate. The toll-speed relationships were approximated to be negative exponential in the selected case. Progressively increasing with GP lane traffic, the tolls varied between $0.77 and $12.64 per use, of which the value of reliability accounted for 24% to 44% and the value of time savings accounted for the remainder. A toll multiplier is designed to deal with HOT underutilization or congestion. The proposed scheme can be applied to dynamic or time-of-day toll adjustments, and is informative for planning and policymaking.

The proposed scheme is traffic responsive. It does not intend to serve as a utility curve for lane choice analysis since the choice behavior is affected by additional factors other than VOR and VOT. Area-specific VOR and VOT should be considered when applying the toll scheme. The tolls are defined as the monetary addition of values of time savings and reliability, i.e., the same weight of unity for both attributes. Different weights can be investigated through surveys and statistical skills. The proposed scheme assumes that the setting of tolls and the adjustment methods are, and can be, strictly econometric and free of political and other "non-rational" influences. Essentially, toll structures are both algorithmic and political. Revealing more background behind the existing HOT cases would complement the rational analysis.

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I-25 Express Lane: Denver, CO. www.dot.state.co.us/cte/expresslanes

I-10W Managed Lanes: Houston, TX. www.hctra.org/katymanagedlanes

I-15 Express Lane: San Diego, CA. fastrak.511sd.com/GettingStarted.aspx

I-95 Express Lane: Miami, FL. www.95express.com

SR-167 Express Lane: Seattle, WA. www.wsdot.wa.gov/Projects/SR167/HOTLanes

I-394/I-35W Express Lane: Minneapolis, MN. www.mnpass.org

I-680 Alameda County Express Lane: Alameda County, CA. www.680expresslane.org

I-85 Express Lane: Atlanta, GA. www.peachpass.com/

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