Examining Potential Travel Time Savings Benefits due to Toll Rates that Vary By Lane

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ABSTRACT

By assigning different toll rates to different lanes during peak traffic hours, the demand for each lane of a road can be optimized. Lanes with lower travel times charge higher toll rates which are paid by those drivers who have higher values of travel time (VTT) and who want to avoid congestion in the other lanes. Conversely, travel time for those drivers with lower values of travel times will increase as they select the lower priced and slower lanes. This research examined toll rates that minimize the total value of travel time spent on the road under such a scenario. The optimum toll rates are dependent on the total road volume and distribution of VTT. The results show that total saved value of travel time can easily reach 11% of the total value of time spent traveling on the lanes when compared to a toll road with a uniform toll rate for all lanes. This savings varies based on many factors including the number of travelers on urgent trips.

INTRODUCTION

Fiscal constraint on transportation infrastructure expenditures has many agencies considering managed lanes (MLs) to optimize the use of those lanes and provide travelers with high values of travel time (VTT) an uncongested alternative. This research expands on that idea and examines a scenario where most lanes of a roadway are managed. This research examines the travel time savings derived from offering different toll rates on different lanes of the same road. This allows those drivers with high VTT to select, and pay for, the lanes with lower travel times. This concept will be tested on the Veterans Expressway in the Tampa Bay area in 2016 (http://www.tollroadsnews.com/node/6250).

To estimate the distribution of vehicles in different lanes with different toll rates, VTT distributions are needed. In this research, distributions developed by Patil et al. (2011) are used. These rates were developed through a survey of travelers along the Katy Freeway in Houston. The Katy Freeway has managed lanes and thus those respondents were already familiar with the option of paying more for a faster trip.

Different toll rates could influence other costs besides travel time because changes in speeds leads to changes in the amount of fuel consumed and emissions produced. However, in many benefit-cost analyses for variable and dynamic tolling, the costs or benefits from changing fuel consumption or emissions were found to be very small compared to benefits from travel time savings (2, 3). Therefore, in this research, only the change in travel time savings is investigated.

LITERATURE REVIEW

Poole (2012) discussed the challenges of freeway pricing and problems of conventional approaches in road pricing. He stated that since uniform pricing treats all travelers in the same way and ignores the variability in travelers' VTT, it overcharges many travelers while undercharging others. Therefore, he concluded that freeway users should be provided with several choices of price and level of service to be able to choose the

option that charges them fairly. He used the term of "multi-pricing" for this pricing approach which can satisfy users and maximize the social welfare (4).

Shamanske (1991, 1993), is one of the first researchers who studied the benefit gained by toll discrimination. However; toll discrimination defined by Shmanske is different from the multi-lane pricing concept investigated here. Shmanske's toll discrimination approach allows those drivers with higher VTT to enjoy a shorter queue and thus shorter waiting time at toll plazas by paying a higher toll. He found that toll discrimination can minimize the total value of waiting time at toll plazas (5, 6). However, electronic toll collection is used now and the concept of toll discrimination at a toll plaza is not applicable. But tolls that vary by lane may have a similar impact.

In this research, the benefits from saving travel time through the use of toll rates that vary by lane are investigated. Therefore, it is critical to use reasonable VTT. Most empirical studies of travel mode choices cannot separate many factors like comfort that affect the mode choice from the value of time (7). As a result, it is more common to use stated preference data for determining VTT (8). Since mixed logit models allow certain parameters in discrete choice models to vary within the population (according to a determined distribution), it was used to derive VTT from stated preference survey data (9).

Many studies conclude that VTT is dependent on income (7, 10). In addition, Patil et al. (2011) found that travelers' value of travel time is much higher when they face urgent situations. They conclude that ignoring higher VTT for urgent trips and classifying them as ordinary trips can greatly underestimate the benefits from saved travel time (1). In order to prevent underestimating VTT and benefits, mixed logit models of the VTT for three income groups and seven travel situations (including an ordinary situation and six urgent situations) developed by Patil et al. are used.

Clearly, having a roadway with different prices for travel on different lanes would have many logistical problems. Enforcement might be possible using closely spaced electronic toll collection readers. If the driver was observed in the higher priced lane by these readers then they would pay the higher toll – even if they had only switched lanes for a short time. However, in cases when there is a lane blockage there would need to be alternative policies in place to allow lane changing.

If the roadway was previously untolled then there would be public opposition to the idea and issues with equity. DeCorla-Souza has investigated potential methods to minimize the equity issue with ideas such as FAIR Lanes (Fast and Intertwined Regular lanes) (11). However, ideas such as FAIR lanes and the one developed in our research come with many potential additional complications. This research is focused on the potential benefits of a "multi-pricing" policy. If the benefits are substantial the next step would be to investigate overcoming the practical hurdles to implementation.

METHODOLOGY

Patil et al. used SP data collected via an Internet survey of Katy Freeway travelers to develop mixed logit models of the VTT for an ordinary travel situation and six different urgent travel situations for three income groups (1). Their estimated VTT distributions for an ordinary trip and five of urgent situations are used in this research (see Table 1). Using these models the distributions of implied VTT for each household income group are obtained. For example, VTT distributions for the high income group are shown in Figure 1. As expected, high income travelers also had the highest VTT. It is interesting to note that low income travelers had higher VTT than medium income travelers. This may be due to time constraints that are placed on the low income travelers, particularly inflexible work starting times.

Traveler Characteristics

To be able to use the VTT distributions shown in Table 1, reasonable assumptions about the percent of drivers in each group of travelers was necessary. In this research, assumptions regarding these percentages were based on a mix of traveler survey data in Houston and census data from Houston. They were as follows:

1- Percent of travelers with low income = 25%,
2- Percent of travelers with medium income = 37%,
3- Percent of travelers with high income = 38%,

4- The percentage of travelers who are facing an urgent trip will vary from 0 percent to 30 percent. For those travelers who are facing an urgent situation, the distribution of urgent situations were arbitrarily set as follows:

- 20% face urgent situation-Important Appointment,
- 20% face urgent situation-Late Appointment,
- 20% face urgent situation-Worry Time,
- 20% face urgent situation-Late Managed Lane,
- 20% face urgent situation-Extra Stops.

TABLE 1 VTT Used in This Research

Situation	Description	High Income Group (greater than US$100,000, annual household income)	Medium Income Group (US$50,000-100,000, annual household income)	Low Income Group (less than US$50,000, annual household income)
Ordinary		8.62 – 8.62 * t_{time}	7.38 – 7.38 * t_{time}	7.95 – 7.95 * t_{time}
Important Appointment (ImpAppt)	Traveler needs to arrive on time for an important appointment/meeting/event	23.23 – 23.23 * t_{time}	16 – 16 * t_{time}	18.95 – 18.95 * t_{time}
Late Appointment (LateAppt)	Traveler is late and in need of the fastest travel alternative	47.69 - 36.92 * t_{time}	27.76 – 21.5 * t_{time}	35.09 – 27.17 * t_{time}
Worry Time	Traveler is worried about arriving on time	30.43 – 20.87 * t_{time}	21.65 – 14.85 * t_{time}	25.03 – 17.08 * t_{time}
Late Managed Lane (LateML)	Traveler had left late since he knows he can take advantages of MLs (or expensive lanes)	20 – 16 * t_{time}	15.25 – 12.2 * t_{time}	17.3 – 13.84 * t_{time}
Extra Stops	Traveler needs to make extra stops on the trip but still needs to arrive on time	9.86 – 9.86 * t_{time}	8.27 – 8.27 * t_{time}	9 – 9 * t_{time}

t_{time} is randomly drawn from a triangular distribution (-1,1) with a mean of 0.

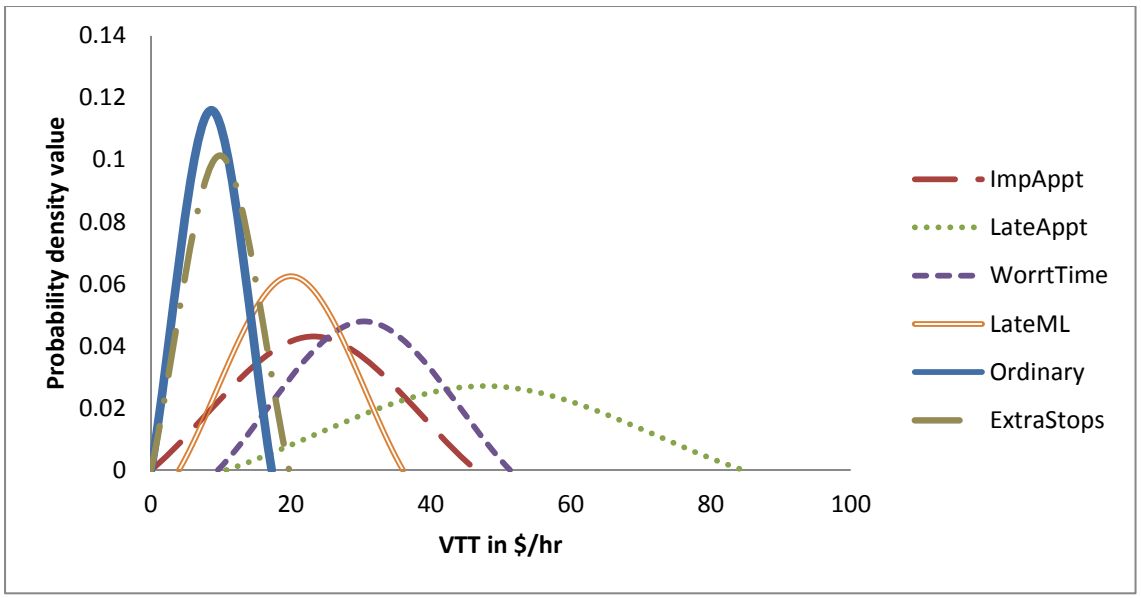

FIGURE 1. VTT Distributions for the High Income Group

These assumptions can be changed to see how travel times are impacted by the number of travelers on each urgent trip situation. However, in this research, these percentages will remain constant as other variables (the percent of total urgent trips and volume of traffic) are varied.

Road Characteristics

In this study a roadway segment with following characteristics was assumed:

1- Length of segment = 10 miles
2- Free flow speed = 75 mph
3- Total number of lanes = 4 lanes in each direction
    - One expensive lane
    - Two moderate lanes
    - One cheap lane

Again, all these characteristics can be changed to examine their impact on travel time from this differential tolling idea.

Travel Time Calculation

In this research, equation 1 is used to calculate travel delay and travel time.

$$T = T_f[\,1 + a * \left(\frac{V}{V_k}\right)^b\,] \qquad (1)$$

Where:

T: Travel time

T_f : Travel time with free flow speed

V: Total volume on the lane(s)

V_k: Capacity of the lane(s)

This function with parameter values a=0.15 and b=4 is known as the Bureau of Public Roads (BPR) function, and with a=0.2 (for freeways) and b=10 is known as the "updated BPR function" (12). The updated BPR function is used to calculate travel time in this research.

Travel Time Saving Calculation

There are 18 groups of travelers (6 different situations for each of 3 income groups), and the objective is to minimize the total value of travel time of travelers (TVTT) on this section of road. If i (1 to18) represents a group of travelers and j (1 to 3) represents a lane category (expensive, moderate and free):

$$TVTT = \sum_{i=1}^{i=18} VTT_i \qquad (2)$$

$$VTT_i = \sum_{j=1}^{j=3} NT_{ij} * TT_j * AVTT_{ij} \qquad (3)$$

Where:

$TVTT$: Total value of travel time ($)

VTT_i: Value of travel time for group i of travelers ($)

NT_{ij}: Number of travelers from group i in lane category j

TT_j= Travel time in lane category j (min)

$AVTT_{ij}$: Average value of travel time for travelers from group i in lane category j ($/min)

$AVTT_{ij}$and $NT_{ij}$are dependent on the toll rates; and $TT_j$is dependent on volume in each lane. Equation 4 is used to calculate TT_j:

$$TTj = T_f\left(1 + 0.2\left(\frac{\sum_{i=1}^{18} NT_{ij}}{N_j * 1800}\right)^{10}\right) \quad (4)$$

Where:

N_j: Number of lanes for lane category j

This research compares a uniform toll rate strategy with a differential (or multi-pricing) toll rate strategy, it should be note that the potential impacts of differential toll rates on demand would not be more than the impacts of uniform pricing. This is because there is a lane that is cheaper than the uniform toll rate when differential toll rates are used. Therefore, some travelers who might have been priced off a toll road would shift to the cheap lane under a differential toll rate strategy. In this paper, uniform pricing does not mean that prices do not vary by time; it means that prices are the same for all lanes. Therefore, if the differential toll rates are found to be more beneficial than uniform toll rates, it can be combined with other types of pricing including variable or dynamic pricing. Excel solver is used to find the toll rates which minimize the total value of travel time.

Next is a simplified example of how optimum toll rates are found. In this example, the only travelers on the roadway are high income travelers who face the urgent situation: they are running late but know a managed lane option is available (Late Managed Lane), instead of having all 18 traveler categories. The pdf of VTT for these travelers can be seen in Figure 1 which is used in equations 5, 6, 7, 11, 12 and 13. Also assume there are 8000 of these travelers in the peak hour and their VTT is distributed as shown in Figure 2.

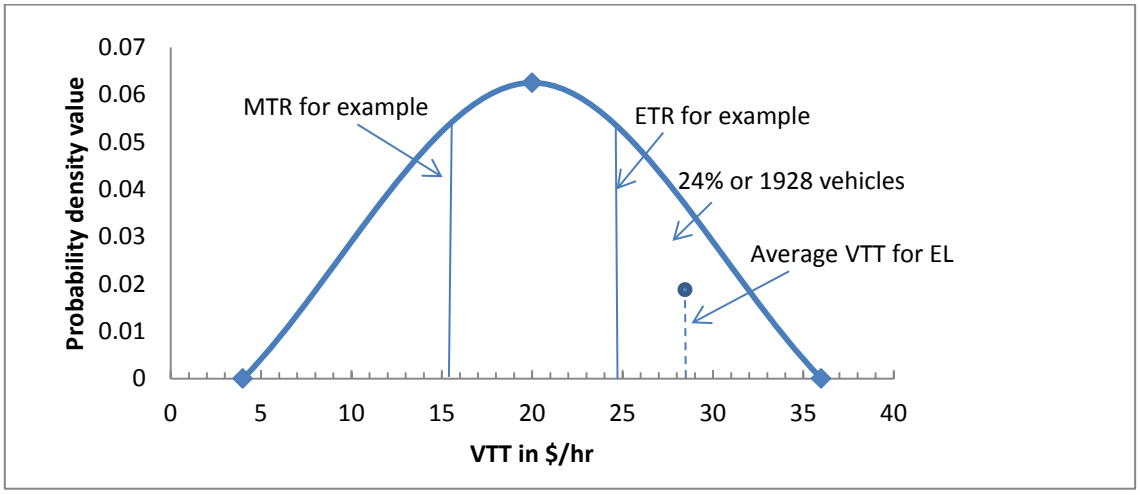

FIGURE 2. VTT Distribution for High Income Travelers who Face the LateML Situation

Figure 2 is derived from the equation for VTT for high income drivers who face LateML situation (see table 1) which is:

$VTT_{(\text{high income\ LateML})} = 20 - 16 * t_{time}$

Where:

t_{time} is randomly drawn from a triangular distribution (-1,1) with a mean of 0.

Therefore, the $VTT_{(\text{high income\ LateML})}$ distribution is a triangular distribution (4,36) with a mean of 20. Thus, the equations for left side and right side of the triangle are:

Left side: (x-4) * 0.0039

Right side: (20-x)*0.0039 + 0.0625

The number of travelers in each lane category can be obtained using equations 5, 6 and 7. It is assumed that travelers with a VTT lower than moderate toll rate will use the cheap lane; travelers with a VTT between moderate and expensive toll rates will use moderate lanes, and those with a VTT higher than expensive toll rate will use the expensive lane. The ratio of travelers in the cheap, moderate and expensive lanes are determined by

the area under the pdf curve for VTT smaller than MTR (equation 5), the area under the pdf curve for VTT between MTR and ETR (equation 6) and the area under the pdf curve for VTT larger than ETR (equation 7).

Lane 1: cheap lane

Lane 2: two moderate lanes

Lane 3: expensive lane

MTR: Moderate toll rate

ETR: Expensive toll rate

MINIMIZE: TVTT= $\sum_{j=1}^{j=3} NT_j * TT_j * AVTT_j$

Subject to:

$$\frac{NT_1}{8000} = \begin{cases} \int_{x=4}^{x=MTR} [(X-4)*0.0039]dx & if\ MTR < \$20/hr \\ 0.5 + \int_{x=20}^{x=MTR} [(20-X)*0.0039+0.0625]dx & if\ MTR > \$20/hr \end{cases} \quad (5)$$

$$\frac{NT_2}{8000} = \begin{cases} \int_{x=MTR}^{x=ETR} [(X-4)*0.0039]dx & if\ ETR < \$20/hr \\ \int_{x=MTR}^{x=20} [(X-4)*0.0039]dx + \int_{x=20}^{x=ETR} [(20-X)*0.0039+0.0625]dx & if\ MTR < \$20/hr, ETR > \$20/hr \\ \int_{x=MTR}^{x=ETR} [(20-X)*0.0039+0.0625]dx & if\ MTR > \$20/hr \end{cases} \quad (6)$$

$$\frac{NT_3}{8000} = \begin{cases} \int_{x=ETR}^{x=36} [(20-X)*0.0039+0.0625]dx & if\ ETR > \$20/hr \\ 0.5 + \int_{x=MTR}^{x=20} [(X-4)*0.0039]dx & if\ ETR < \$20/hr \end{cases} \quad (7)$$

Using the number of travelers in each lane category and travel time function (equation 1) travel time in each lane category is calculated (equations 8, 9 and 10). The average value of travel time for travelers in each lane category can be obtained using equations 11, 12 and 13.

$$TT_1 = \frac{10}{75} * 60 * \left(1 + 0.2\left(\frac{NT_1}{1*1800}\right)^{10}\right) \quad (8)$$

$$TT_2 = \frac{10}{75} * 60 * \left(1 + 0.2\left(\frac{NT_2}{2*1800}\right)^{10}\right) \quad (9)$$

$$TT_3 = \frac{10}{75} * 60 * \left(1 + 0.2\left(\frac{NT_3}{1*1800}\right)^{10}\right) \quad (10)$$

The average value of travel time for travelers in the cheap, moderate and expensive lanes are the centroid of the area under the pdf curve for VTT smaller than MTR (equation 11), the centroid of the area under the pdf curve for VTT between MTR and ETR (equation 12) and the centroid of the area under the pdf curve for VTT larger than ETR (equation 13).

$$AVTT_1 * 60 = \begin{cases} \frac{\int_{x=4}^{x=MTR} X[(X-4)*0.0039]dx}{NT_1/8000} & if\ MTR < \$20/hr \\ \frac{0.5\times 14.7 + \int_{x=20}^{x=MTR} X[(20-X)*0.0039+0.0625]dx}{NT_1/8000} & if\ MTR > \$20/hr \end{cases} \quad (11)$$

$$AVTT_2 * 60 = \begin{cases} \frac{\int_{x=MTR}^{x=ETR} X[(X-4)*0.0039]\,dx}{NT_2/8000} & if\ ETR < \$20/hr \\ \frac{\int_{x=MTR}^{x=20} X[(X-4)*0.0039]dx + \int_{x=20}^{x=ETR} X[(20-X)*0.0039+0.0625]dx}{NT_2/8000} & if\ MTR < \$20/hr, ETR > \$20/hr \\ \frac{\int_{x=MTR}^{x=ETR} X[(20-X)*0.0039+0.0625]dx}{NT_2/8000} & if\ MTR > \$20/hr \end{cases} \quad (12)$$

$$\text{AVTT}_3*60 = \begin{cases} \dfrac{\int_{x=ETR}^{x=36} X[(20-X)*0.0039+0.0625]dx}{NT_3/8000} & if\ ETR > \$20/hr \\ \dfrac{\int_{x=MTR}^{x=20} X[(X-4)*0.0039\ ]dx+0.5\times 25.3}{NT_3/8000} & if\ ETR < \$20/hr \end{cases} \quad (13)$$

The minimum TVTT will be obtained by setting the ETR at $24.9/hr and the MTR at $15.6/hr. The benefit is the value of travel time saved using these toll rates versus a scenario where all vehicles pay the same or no toll (equation 14). Table 2 shows the travel time and toll for each lane category in this example.

$$Benefit = TVTT_{uniform\ toll} - TVTT_{differential\ tolls} \quad (14)$$

$$TVTT_{uniform\ toll} = 8000 * \left[\frac{10\ mile}{75\ mph} * 60\ min * \left(1 + 0.2 * \left(\frac{8000}{4 * 1800}\right)^{10}\right)\right] * \frac{\$20}{hr} * \frac{1hr}{60\ min}$$

$$\rightarrow\ TVTT_{uniform\ toll} = 8000 * 12.59 * \frac{20}{60} = 33570$$

$$TVTT_{differential\ tolls} = 1928 * 11.19 * \frac{28.59}{60} + 3981 * 12.37 * \frac{20.19}{60} + 2091 * 15.16 * \frac{11.71}{60} = 33038$$

TABLE 2 Optimum Tolls and Travel Time for the Example

Differential toll rates strategy						Uniform toll rate strategy		
Benefit ($/h)	Lane Category	Volume	Average value of travel time ($/h)	Travel Time (min)	Relative Toll ($)	Volume on each lane	Travel time (min)	Average value of travel time ($/h)
	Expensive Lane	1928	28.59	11.19	1.65			
	Moderate Lanes	3981	20.19	12.37	0.72			
532	Cheap Lane	2091	11.71	15.16	-	2000	12.59	20.00

The tolls found here are the relative toll rates which means that the moderate toll and expensive toll should be $0.72 and $1.65 more than the cheap toll respectively. The actual toll rates are dependent on the uniform toll rate that was charged previously. The moderate toll rate could be set as the same price as previous uniform toll rate. Then, the expensive toll rate and cheap toll rate can be found using the relative toll rates shown in the table 2. For example, if the uniform toll rate was $2 previously, the cheap, moderate and expensive toll rate would be $1.28, $2 and $2.93, respectively.

This example only reduced the value of time spent traveling by 1.6% ($532/$33570). These benefits will increase when including more variety in VTT and groups of travelers as outlined in the results section.

RESULTS

The above approach was then expanded for all 18 groups of travelers. The total benefit for different traffic volumes and different percentages of urgent trips was calculated. Figure 3 and Table 3 show how total benefits change with respect to the change in total vehicle volumes and the percentage of urgent trips.

As expected, the benefit increases as congestion increases and as more travelers face urgent trips (since their VTT increases). Travel times on the moderate lanes is similar to the travel time with a uniform toll rate. Therefore, the change is primarily between travelers moving to the expensive and free lanes. Travelers in expensive lanes benefit most from the different toll rate strategy, while travelers in free lanes lose some travel time by moving to this strategy. Overall, because of the high VTT for travelers in expensive lanes and low VTT for travelers in free lanes, there is a net benefit in using the differential toll rates strategy.

FIGURE 3 Benefits of the Differential Toll Rate Strategy by the Percent of Urgent Trips (Volume=8000 vph)

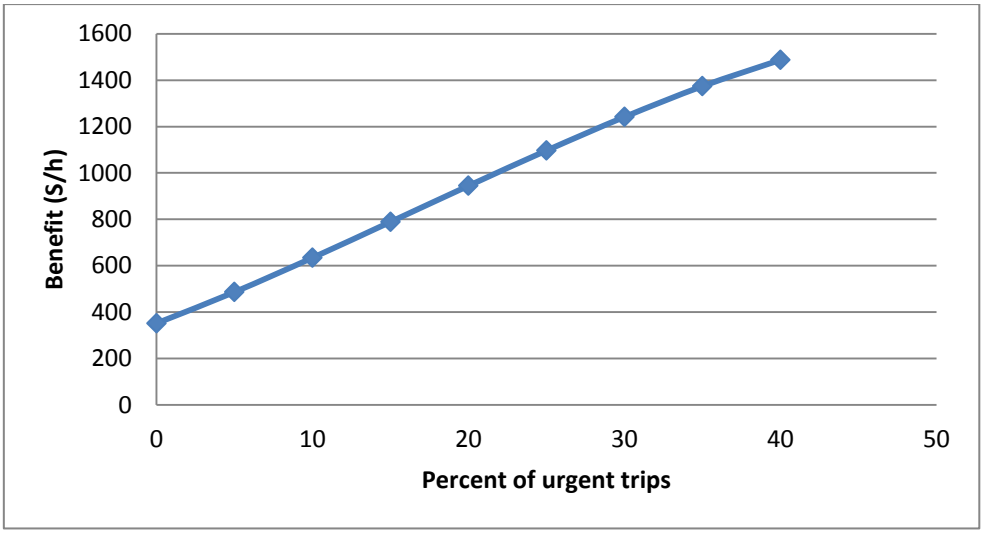

TABLE 3 Differential Toll Rates Strategy Results

	Volume (vph)	Total Benefit ($/h)	VTT Saving (%)	Travel Time with Same Toll Rates (min)	Relative Toll for Moderate Lane ($)	Relative Toll for Expensive Lane ($)	Cheap Lane Travel Time (min)	Moderate Lane Travel Time (min)	Expensive Lane Travel Time (min)
30% urgent trip	7000	286	2.19	9.21	0.16	0.49	10.63	9.21	8.52
	8000	1241	6.09	12.59	0.60	1.88	18.00	12.59	9.97
	8500	2418	8.56	16.41	1.11	3.45	26.33	16.41	11.62
	9000	4535	10.86	22.90	1.96	6.10	40.47	22.90	14.40
	9500	8219	12.72	33.59	3.36	10.48	63.75	33.59	19.00
20% urgent trip	7000	217	1.88	9.21	0.14	0.40	10.49	9.21	8.55
	8000	945	5.23	12.59	0.52	1.52	17.46	12.59	10.10
	8500	1840	7.35	16.41	0.94	2.79	25.34	16.41	11.86
	9000	3451	9.33	22.90	1.67	4.94	38.72	22.90	14.83
	9500	6255	10.93	33.59	2.87	8.47	60.74	33.59	19.73
10% urgent trip	7000	146	1.45	9.21	0.12	0.32	10.33	9.18	8.62
	8000	635	4.03	12.59	0.44	1.22	16.87	12.50	10.36
	8500	1236	5.67	16.41	0.81	2.25	24.26	16.25	12.34
	9000	2318	7.19	22.90	1.43	3.98	36.80	22.61	15.68
	9500	4202	8.42	33.59	2.46	6.83	57.45	33.08	21.19

The benefits range a great deal depending on the variety of VTT in traffic. In the example, there was only a $530 net benefit. Using the same traffic condition (8000 vph) but all 18 groups of travelers with 20 percent facing urgent trips, this benefit increases to $945, or 5.2 percent of the value of travel time. It is not until the facility becomes congested do benefits become substantial. For example, at 9000 vph with 20 percent urgent

trips the total value of time spent traveling in the uniform tolling scenario is $36982 and in deferential tolling strategy is $33531, a saving of 9.3%. The savings increase to 10.9% as the percent of urgent trips increases to 30 percent.

As with Table 2, the toll rates provided in Table 3 are set relative to the toll in the cheap lanes. The table shows rates with respect to a free cheap lane, but the results would be the same if all three lane categories charged another dollar. This is because of the simplifying assumption that demand is fixed for each scenario and did not depend on the toll. Clearly demand would change based on the toll rate. However, if the median lane toll price were set at the same rate as a toll road that previous operated with uniform rates, the impact on demand would be minimal.

TOLL ROAD EXPRESS LANES EXAMPLE

In this second example, a conventional 5 lane (per direction) toll facility is converted into a toll facility with 2 express lanes (more expensive lanes) and 3 cheap toll lanes. All other assumptions (10 mile length, updated BPR relationship between speed and flow, 18 groups of travelers, etc.) remain the same. It is assumed that 20 percent of travelers are facing urgent travel situations. The analysis indicates that there are VTT benefits from this strategy versus a toll facility with a uniform toll rate on all lanes (see Table 4).

TABLE 4 VTT Savings for Express Lanes on a Toll Road

Volume (vph)	TVTT with Uniform Toll ($)	TVTT with Differential Toll Rates ($)	VTT Saving (%)	Relative Toll for Expensive Lanes ($)	Travel Time with Uniform Toll (min)	Travel Time for cheap Lanes (min)	Travel Time for Expensive Lanes (min)
10000	21199	20480	3.39	0.54	11.81	13.40	10.20
11000	31929	30233	5.31	1.17	16.18	19.58	12.71
11500	40586	38056	6.23	1.67	19.67	24.52	14.72
12000	52542	48831	7.06	2.34	24.40	31.22	17.45
12500	68939	63581	7.77	3.24	30.74	40.19	21.10

CONCLUSION

In this research, VTT distributions developed by Patil et al. (1) were used to investigate the possible benefits of different toll rates versus a uniform toll rate for a roadway. In the differential toll rates strategy the roadway is divided into cheap, moderate and expensive lanes. In the uniform toll rates strategy all lanes have the same toll rate (which could also be free). It was found that significant benefits could be gained from the differential toll rates strategy for a congested roadway. The benefit increases as the volume and numbers of travelers facing urgent trips increases. For example, when the volume is 9000 vph in four lanes and 20 percent of travelers are facing an unusual/urgent trip, the total value of travel times could be reduced by 9.3% using differential toll rate strategy.

FUTURE STUDIES

The estimated benefits have a direct relationship with the travel time function. Therefore, a sensitivity analysis on the influence of the parameters of this function could be undertaken. Also, real travel time data for a similar roadway could be used to calibrate these parameters. Moreover, the assumption that travelers with different VTT use the designated lane may be unrealistic; this assumption would be more close to reality if travelers know the travel time of each lane in advance. Studies are needed to find how actual travel time saved is valued differently from what travelers believe they will save by choosing each lane.

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