Investigate Attractiveness of Toll Roads

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INVESTIGATE ATTRACTIVENESS OF TOLL ROADS

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16. Abstract
HOT facilities are used as a solution for congestion mitigation instead of constructing or expanding the capacity of existing roadways. Although toll roads modeling has been researched for a long time, High Occupancy Toll (HOT) modeling is relatively new. Due to its feature of dynamic rates and multiple access points along the route where drivers can buy in and buy out of the HOT facility easily, the drivers' reaction to the toll rate changes varies from that on a traditional toll road and is more complicated. The percentage of SOV drivers who choose to pay for HOT lane usage is not a monotonously decreasing curve related to toll rate because the dynamically updated toll rate on a HOT lane is directly related to the traffic volume and corresponding congestion level. In this study, the data from SR-167 in the state of Washington are analyzed to study driver responses in responses to the toll rate. The percentage of SOVs, who need to pay for using the HOT facility, is analyzed against variables including toll rate, volume, speed, and speed reliability in both the HOT lane and General Purpose (GP) lane. Two sets of logistic models are fitted for the data from the year of 2008 and 2010. The results showed that the significant variables include: speed in the GP lanes, speed reliability in the GP lanes, and the traffic volumes in the GP lanes. The toll rate is only significant for the year of 2010. There is a significant ramp-up effect from 2008, the opening year, to 2010, two years after the facility opened to traffic.

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Abstract

HOT facilities are used as a solution for congestion mitigation without new constructions to expand the capacity of existing roadway. Although toll roads modeling has been researched for a long time, HOT modeling is relatively new. Due to its feature of dynamic rate and multiple access points along the route where drivers can buy in and buy out of the HOT facility easily, the drivers' reaction to the toll rate changes varies from that on a traditional toll road and is more complicated. The percentage of SOV drivers who choose to pay for HOT lane is not a monotonously decreasing curve related to toll rate because the dynamically updated toll rate on a HOT lane is directly related to the traffic volume and corresponding congestion level. In this study, the data from SR-167 in the state of Washington are analyzed to study driver responses in responses to the toll rate. The percentage of SOVs, who need to pay for using the HOT facility, is analyzed against variables including toll rate, volume, speed, and speed reliability in both the HOT lane and General Purpose (GP) lane. Two sets of logistic models are fitted for the data from the year of 2008 and 2010. The results showed that significant variables include: Speed in the GP lanes, speed reliability in the GP lanes, traffic volumes in the GP lane. Toll rate is only significant for the year of 2010. There is a significant ramp-up effect from the year of 2008, the opening year, to 2010, two years after the facility opened to traffic.

Introduction

As a potential travel demand management strategy, congestion pricing is an effective tool chosen by many state and local transportation agencies to limit peak hour traffic and shift traffic to other roads, different departure time, or other modes. The modeling of traffic demand in response to toll rates has been a research subject for a long time (Zhang et al., 2008, Marlon and Chalermpong, 2011, Verhoef, 2005). Conventional modeling method usually includes a large scale stated preference survey where the value of time (VOT) is identified and utility function will be used to model the likelihood of travelers' choice of toll roads given a fixed toll rate. Common variables include VOT, trip purposes, trip length, time of day, income level, age, gender, etc. (Zmud et al., 2007).

As one of the earliest studies on demand elasticity in relation with time-varying prices, Gifford and Talkington used the toll rates, gas price and corresponding day of week as the independent variables to model the daily traffic demand (Mon-Thursday, Friday, Saturday, and Sunday as dependent variables, individually). They found that day-of-week cross elasticity is complementary and their findings lend empirical support to claims that time-varying prices may be a viable strategy for managing traffic demand.(Gifford and Talkington, 1996). Cain et al studied the impacts of variable pricing on the temporal distribution of demand to investigate the role of variable pricing as the demand management tool. They found that at the aggregate level, program implementation had a minimal impact on the overall distribution of demand. Demand for peak-period travel remained relatively unaltered, and active peak spreading was not observed. However, the disaggregate level analysis showed significant shift of traffic from peak hour to peak hour shoulders, where a discount of toll rate is applied (Cain et al., 2001). Du et al. (Du et al., 2013) analyzed the traffic data before and after the implementation of a toll change on the San Francisco Oakland Bay Bridge and concluded that the toll change shifted the time of day travel demand with an increase in non-peak hour trips and a decrease in peak hour trips. Speed increased significantly after the toll changes, especially in a short-term observation period. Bell et al. (Bell et al., 1999) studied the diversion of traffic using macroscopic and microscopic simulation and concluded that the diversion of traffic were affected by the combination factors of toll, distance of the alternative route, and level and congestion of alternative route and the toll route.

The researches on variable tolls are related to the High Occupancy and Toll (HOT) facilities, where much less research has been done. HOT is where a High Occupancy Vehicle (HOV) lane is converted to a toll lane for single occupancy vehicle (SOV) drivers while the HOVs can use the lane free of charge. The idea of HOT develops on the fact that majority of the HOV lanes in US have been underused (Chu and Benouar, 2007, D., 1998). The first HOT lane is on SR-91 in California and the lane opened to traffic in 2001. Now there are around 20 HOT facilities in US and many are under construction. Features of HOT lanes are that: 1) They are free for HOV users; 2) The toll is dynamically changed according to traffic; 3) Toll rate usually updates from every 5 minutes to 15 minutes; 4) Since majority of the HOT facility is built in an existing HOV lane side-by-side with general purposes (GP) lanes, such facilities usually provide multiple access locations along the road for users to get in and out of the lane conveniently. These features ensures the HOT facilities to be a very flexible solution to congestion and a convenient tool in improve network efficiency without extra new constructions. However, they also bring challenges in forecasting and estimating traffic and revenues for such facilities, especially long term forecasting. There are still many questions stay unclear: What will drivers react when they see a toll rate showing up on the bulletin board on the road? Will the demand shift to free hours? Will people choose to car-pool? Due to the multiple access points and that the location of HOT lane alongside with general purpose lanes, the decision of using HOT facility or not can be made and changed in the middle of the traveling, instead of at the commence of a trip. Consequently, drivers' responses to the toll rate does not necessarily follows a strictly monotonously curve as assumed. The flexibility to buy in and out of the HOT lane during traveling made the drivers' choices more unpredictable. Although there have been many previous researches investigated the tolling strategies and evaluate the HOT lane system performance, they are from the theoretical or practical point of view for all HOT lanes in general.(J. and Burris, 2005, Chum and Burris, 2008, Janson and Levinson, 2014, WADOT, 2014, Wang et al., 2012, Halvorson et al., 2006, Yin

and Lou., 2007, Zhang et al., 2008, Burris et al., 2012a, Burris et al., 2009, Burris et al., 2012b, Wood et al., 2014). Some previous researches have been conducted to find the optimum toll rates for HOT lanes. A straightforward method adopted by majority of the HOT lane facilities is to create a look-up table. The toll rate will be decided by looking up the corresponding toll rate to the traffic condition in the HOT lane, measured either by density or speed. The problem is that the toll setting is heuristic in nature and is required to be feasible to be used in field. Typically the look up table uses a fixed scaling rate with the difference between existing density/flow with the desired density/flow to generate the toll rate for the next time period. However, with the complexity of human nature, to choose or not to choose a managed lane is not a simple question that can be answered using solely Value of Time (VOT), utility function, and/or time savings. Many research argued that the perceived travel time saving is not necessary accurate (Peer et al., 2014). In addition, the lookup table is based on real time measured in-field density or flow rate, which has accuracy issue when they are need in a relatively high updating frequency as input data to be fed into the toll rate updating process.
In summary, multiple factors, such as value of time, trip purposes, departure time and arrival time resilience, configuration of the access points, local economic conditions, traffic compositions, population distribution, and gas cost, will all contribute to the percentage of traffic diverts to the HOT lane (Wang et al., 2012). It is essential to first identify the users' reaction to the HOT tolling schemes and understand what factors play a role and how much they will affect driver's choices. For example, there have been research found that the demand curve for HOT lane is, on the contrary of the previously held assumption, a upward sloping curve to the increased toll (Janson and Levinson, 2014, Beggs, 2010). Due to the fact that many HOT facility adopts a dynamic toll rate, meaning that the toll rate is updating very several minutes to maintain a density or speed goal in the HOT lane, the toll rate is not only a tool to control traffic entering the HOT lane, but also the result of the current traffic status. Therefore, drivers are not only respond to a toll rate, they may also use the toll rate as an indicator of upcoming congestion level. The compound relationship makes the percentage of the SOVs who choose to pay for usage of the HOT facility not as straightforward as a regular fixed toll road.

Problem Statements

The accuracy of estimating and forecasting revenue and traffic for HOT facilities has always an issue noted by many. According to a research conducted by Department of Infrastructure and Transportation of Australian Government (Transport, 2010), the overestimation of toll road forecasting model is very common. The reasons they found include: Network coding accuracy (node and link attribute); speed-flow curve used to reflect the characteristics of toll and toll-free roads; and static traffic assignment algorithm is not applicable to variable tolling where shifts in traffic between periods are expected. They also stated that the distribution of users by values of time has been found to be non-symmetric with long right tail. Therefore, the number of users who are actually willing to pay a toll would be fewer than the case when a normal distribution is assumed. In the report of Prozzi et al. (Prozzi et al., 2010), they mentioned the existing problems regarding predicting traffic volume and revenue for toll roads including the unreliability of data source, deficits of forecasting models used by consultants, inaccurate assumptions in traffic and revenue (T&R) calculation approaches, and little or no discussion for key variables that could introduce uncertainty. They suggested that a schematic of the T&R approach detailing the various variables considered, their interaction with other variables, and when these variables are considered in the T&R modeling process. According to the Compass Handbook of ICT solutions, "The operating characteristics of HOT lane projects pose unique challenges in the revenue projection, given the volatility of the typical users of these facilities and the large uncertainty related to how key decision making characteristics will evolve in the future. Revenue for the SR 167 HOT (Washington State, USA) lanes continues to increase and has exceeded operating costs since April 2011, however the project's primary objective remains unchanged: congestion management. HOT lanes continue to help reduce congestion and maintain free-flow traffic conditions in this corridor. Generating revenue is an added benefit. Extra revenue is invested back into the corridor but must first be appropriated by the Legislature. As far as the

Virginia Beltway project, the design and build contract alone is US$1.4 billion, while the total cost is around US$1.9 billion." (Bielefeldt, 2011) In the research of Wood et al. and Burris et al., there is little difference in the willingness to pay between the groups with different frequency of HOT lane using. Travelers are buying their way into the HOT facility for more than just travel time saving, but also other factors.

It is important to forecast the traffic and revenue of toll projects due to fiscal and political reasons. Therefore, to more accurately predict the traffic and revenue for HOT facilities so that the construction and management of these facilities can be better organized, it is essential to first understand the reactions of users to dynamic toll roads. Typical private consulting companies estimate the traffic and revenue for toll projects by the steps shown in Figure 1:

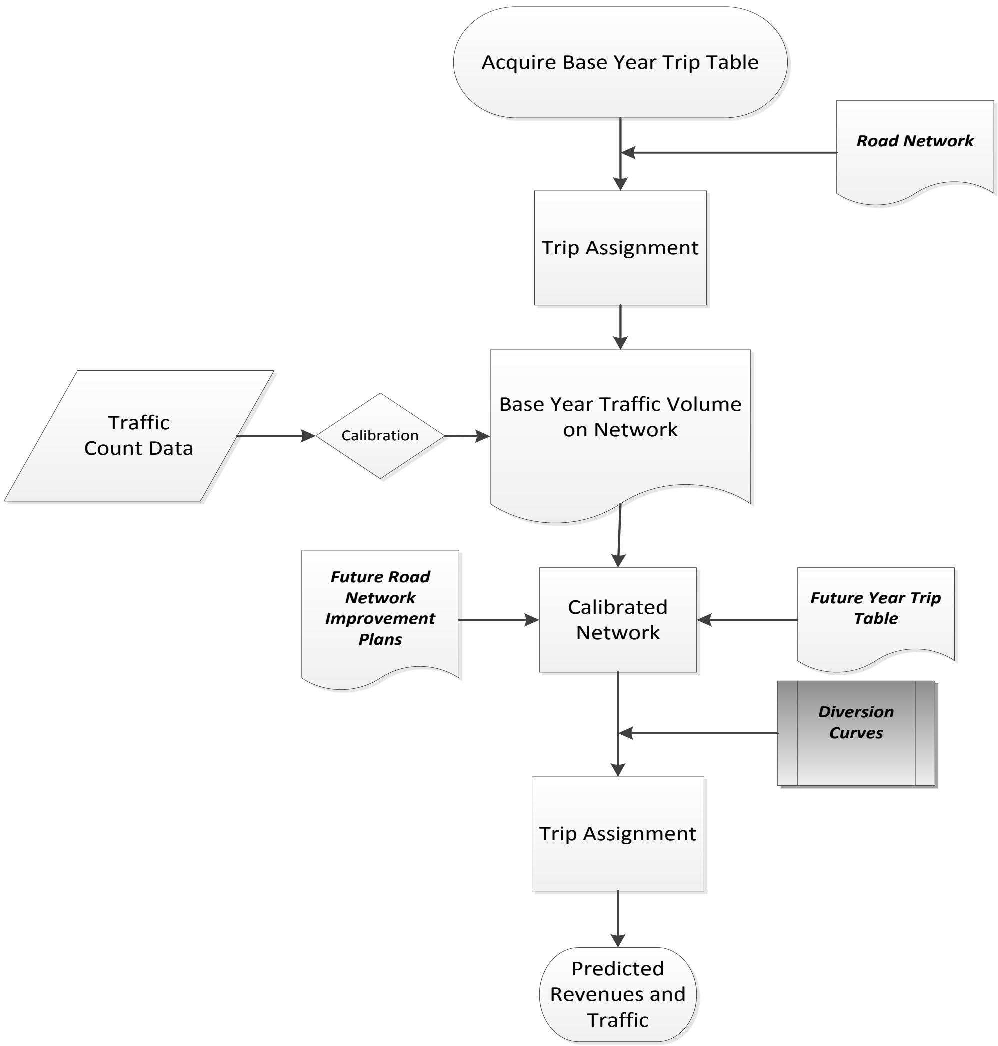

Figure 1 Procedure of Forecasting Revenue and Traffic

The key reason is as shown in the black box in the figure above, namely "diversion curve". In general, diversion curves will be developed depending on potential factors that will affect the traffic demand. Those factors may include but not limit to: social economical features of the area and road users, road class of the toll roads, magnitude of the congestion, other available travel modes etc. Before the HOT facility was open to public, the diversion curves will be developed using such factors. However, results of the traffic and revenue forecasting, as stated before, are far from satisfactory.

Modeling demand changes for HOT facility is a very challenging topic due to the compounded interaction of causes and results of diversion of traffic and the toll rate. As illustrated before, HOT facilities usually have a very complicated toll rate calculation system that aims at maintaining a speed and/or density goal in the HOT lane. The toll rate is decided by the density and speed, while at the same time changes the density and speed. The three parts are interacting and influencing upon each other shown in Figure 2. This interaction makes the conventional method of using travel time saving to model the willingness to pay not as strong as in the case of fixed toll rate facilities.

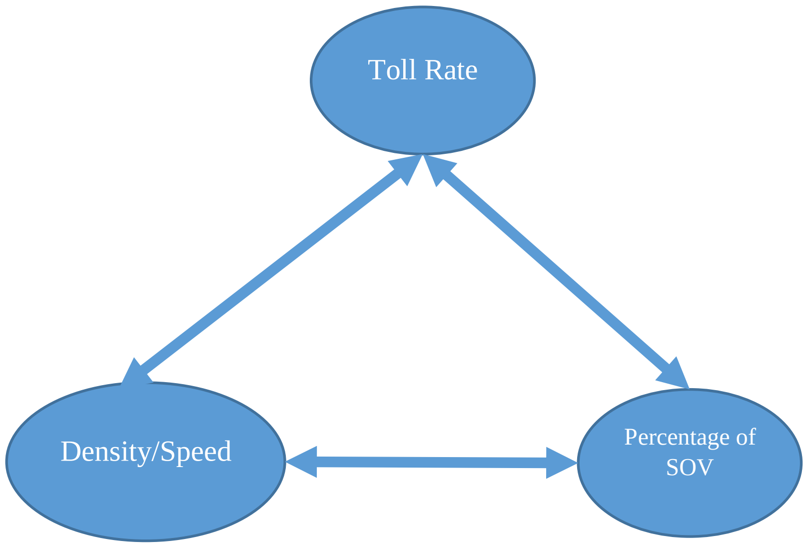

Figure 2 Compound Factors for HOT Lane

It is suggested by previous studies that different trip purposes, trip makers, and trip distances shall all be taken into consideration because they are factors affecting the value of time. However, in the case of HOT lanes, the dynamic toll rate is updated in a very short time period and it is unrealistic to obtain such detailed data in real time. The toll rate and diversion rate for HOT, therefore, will be more sensitive and vary more rapidly.

Fortunately, now with multiple HOT facilities already in operation for multiple years, now it is feasible to look back at the historical data to see the mechanism working behind the scene.

In this report, the traffic features on the SR167 are examined. Data from the opening year, 2008, are analyzed against the traffic volume and toll information in the year of 2010 to explore the behavior of SOV drivers in the presence of dynamic tolls.

Methodology and Model

Study Site

The SR 167 runs northbound and southbound on approximate 10 miles between Renton and Auburn. HOV lanes on SR167 had available space during peak-period commute times, so the WSDOT saw HOT lanes as a tool to increase vehicle throughput without reducing the level of service by carpools and transit. There are two general purpose (GP) lanes in each direction. The GP lanes are free and open to all traffic all the time. The HOT lane is running side-by-side with the GP lanes. Access in and out of the HOT lanes is restricted at designated. High occupancy vehicles (HOV) can use the HOT facility free of charge all the time. Single occupancy vehicles (SOV) will need to pay a toll (WADOT, 2014). The toll rate updates according to traffic condition. It may change as frequently as every 5 minutes to ensure the free flow status of the HOT lane. Figure 3 shows the SR 167 location and configuration. SR 167 opened to traffic in May, 2008.

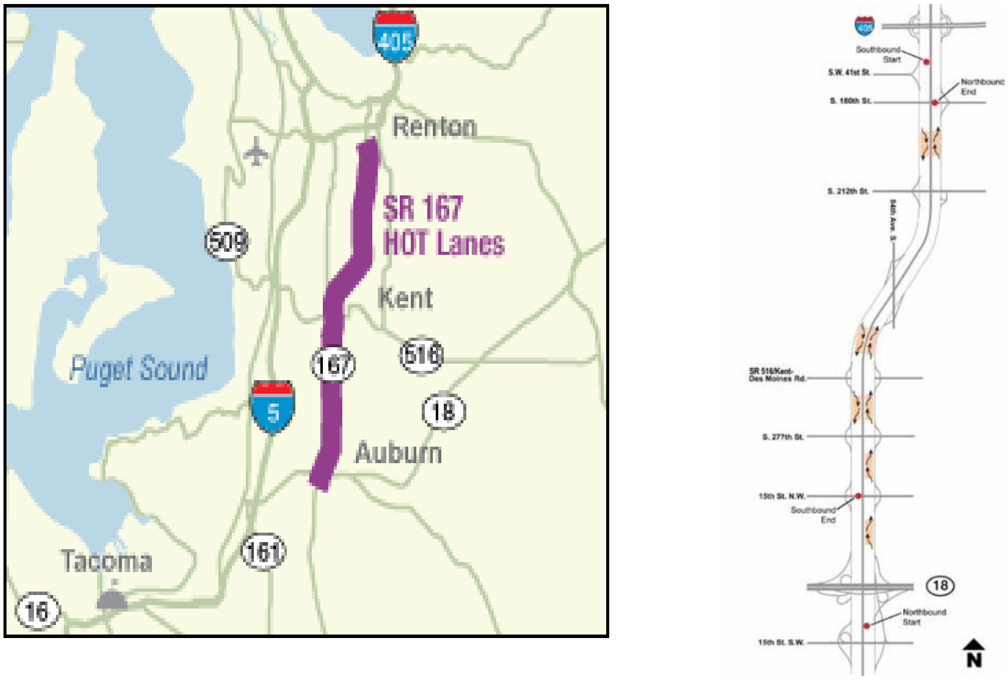

Figure 3 SR 167 Configuration[1]

Data Descriptions

Two data providers in the WA DOT were contacted for this project and two sets of data were obtained from them: A) Loop detector data where the general purpose lane (GP) traffic volumes and speed data extracted from CDR (a traffic data management and aggregate tool developed by WADOT) and aggregated to 5 minute intervals; B) Transponder data where the HOT lane traffic volume, speed, and toll rate data at the frequency of 5 minutes from SR 167 HOT management authority.

To make the two sets of data comparable, required from the two sources include data in June, August, October, and December of 2008 (the year the HOT project started to operate) and the same months in 2010. SR167 adopts a dynamic tolling system. Toll rates may range from $0.50 to $9.50 in the year of 2008 and $0.5 to $4.5 in the year of 2010.

Data Explorations

Since the data are from two different sources, the two sets of data are first compared to ensure the consistency and filter out errors.

[1] Pictures source: http://www.wsdot.wa.gov/NR/rdonlyres/C198671E-7B2F-4186-9912-A41A0B274103/0/SR167_AnnualPerformanceSummary_113011_FINAL_WEB.pdf

Loop Detector Data

Data cleaning

Missing data is the biggest challenge that loop detector data have. In our case, the rule of thumb is to use the occupancy as the indicator: Whenever there is a non-zero occupancy data, there should be a valid larger than zero traffic count. Zero volume only is accepted as validate data when the occupancy is zero simultaneously. Figure 4 shows the average hourly traffic volume in the NB section 6. As can be seen, the NB section 6 has an extended peak hour starting from 5am to 4pm.

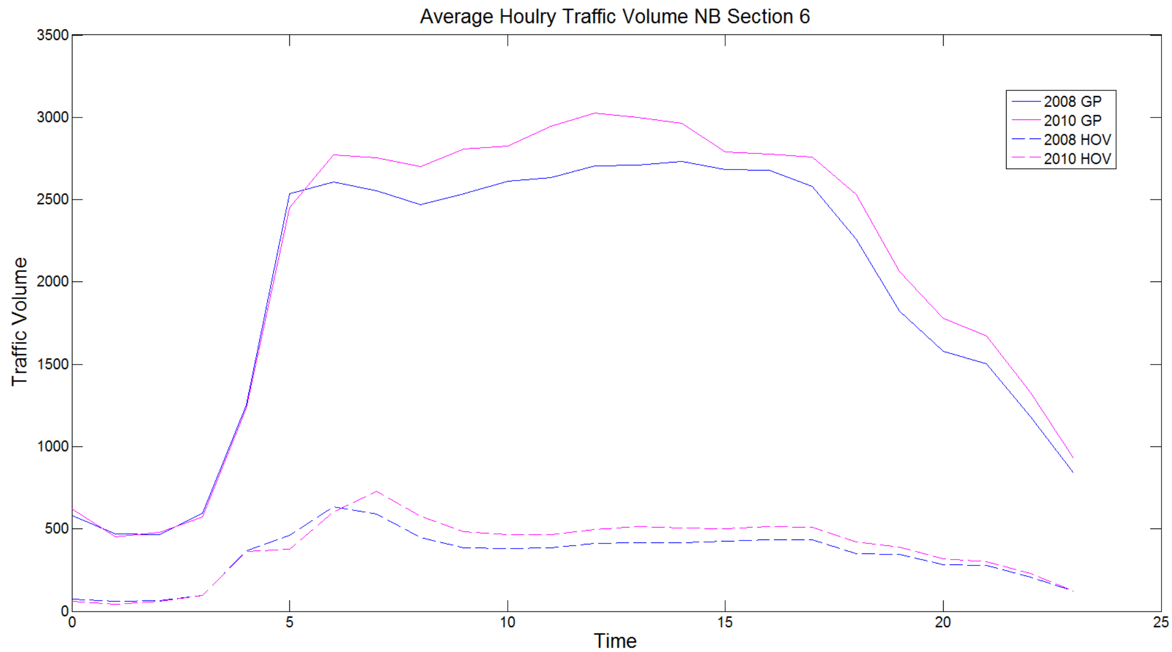

Figure 4 Data Collected Using Loop Detector

Transponder Data

Data cleaning

Transponder data include the following information at the resolution of 5 minutes: Toll rate, SOV who paid to use the HOT lane, HOV counts that can use the HOT lane for free, and the spot speed of vehicles driving in the HOT lane.

Consistency of Loop Detector Data and HOT Data

Since the data analysis involves combing of two data sources, it is vital to ensure the consistency of the two data sources. Therefore, the traffic volume in the HOV/HOT lane from the loop detector is compared with the traffic volume counted by the automatic transponder in the HOT lane. Since the toll project opened to traffic from August 2008, the traffic volumes of August, October and December are averaged over and the plot below shows results of from the two data sources. As can be seen from Figure 5 that the two data sources are very compatible to each other.

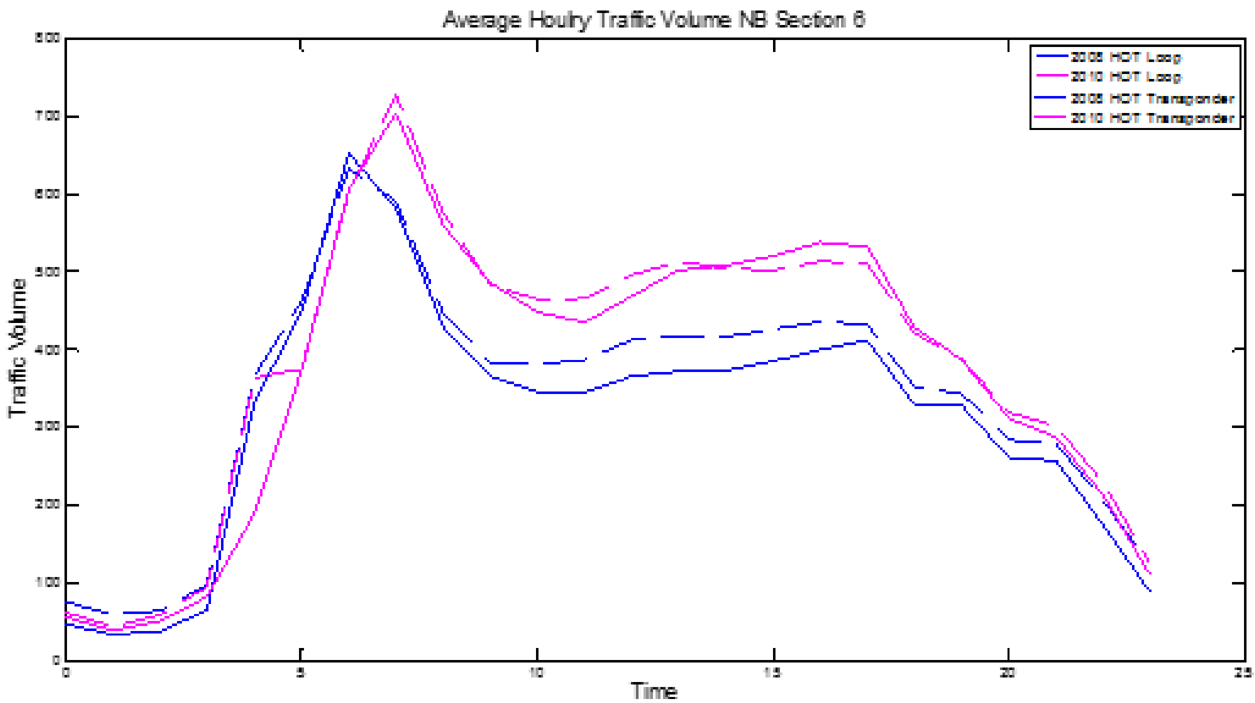

Figure 5 Data Consistency

Data Exploration

The mean percentage of valid Automatic Vehicle Identification (AVI), which is the percentage of single occupancy vehicles who paid the toll to use the HOT lane, is plotted against the toll rate. Figure 6 and Figure 7 show the relationship of SOV usage and the toll rate in the year of 2008 and 2010, respectively. It can be seen that, unlike previously assumed, with the increasing of the toll rate before it reaches \$2.5, the percentage of SOV chose to pay increases. The paid population started to decrease after the toll rate increases further above \$2.5. A similar pattern is observed in the year of 2010.

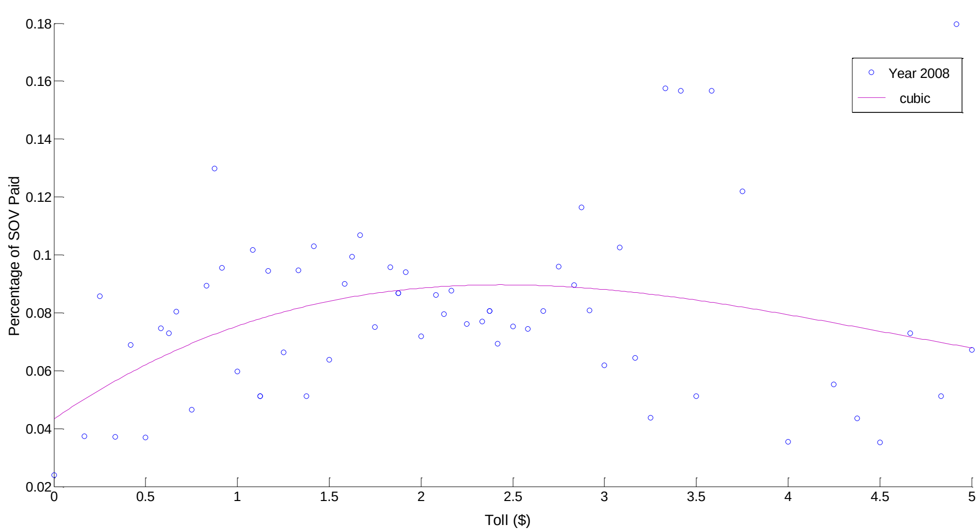

Figure 6 Toll Rate and Percentage of SOVs in 2008

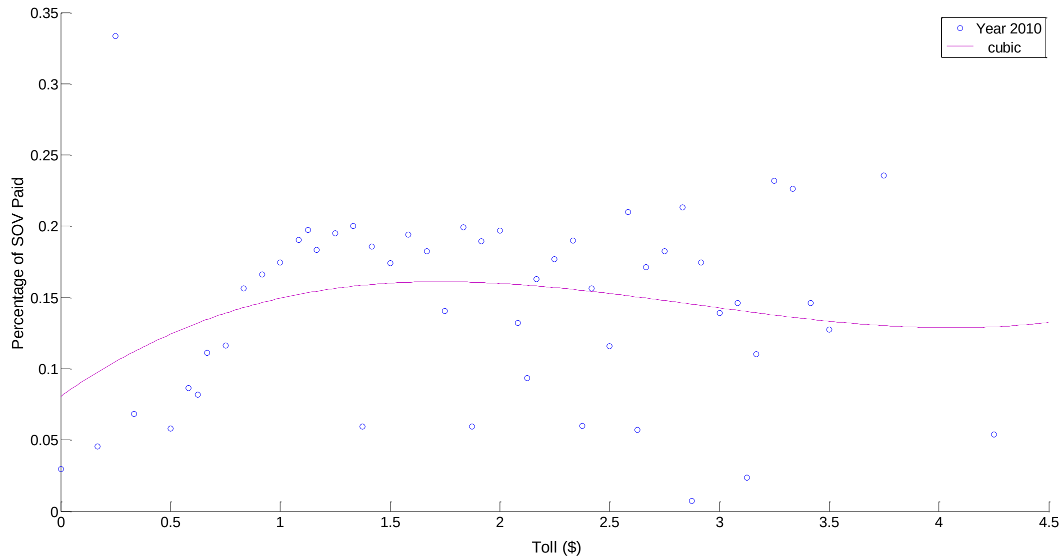

Figure 7 Toll Rate and Percentage of SOVs in 2010

The relationship of SOV percentage with the traffic volumes is explored next. As can be seen Figure 8, there is a similar trend observed in the relationship while plotting the diversion rate with the traffic volume. A four stage trend is observed: First, when the volume stays low, diversion rate stays stable; second, when the volume increases around the capacity, the diversion rate increases dramatically; third, during the congestion level the diversion rate start to be stable; and lastly, when the traffic condition reaches the over-saturated stage, the diversion rate drops. Although the trend is very similar, it can be seen from the figure that the percentage of SOVs chose HOT facility is significantly higher in the year of 2010 than the year of 2008. Figure 9 illustrates the percentage of SOV vehicles in the HOT lane changes over the 2 years. The percentage more than doubled when the traffic flow rate is above 1400 veh/hour/lane.

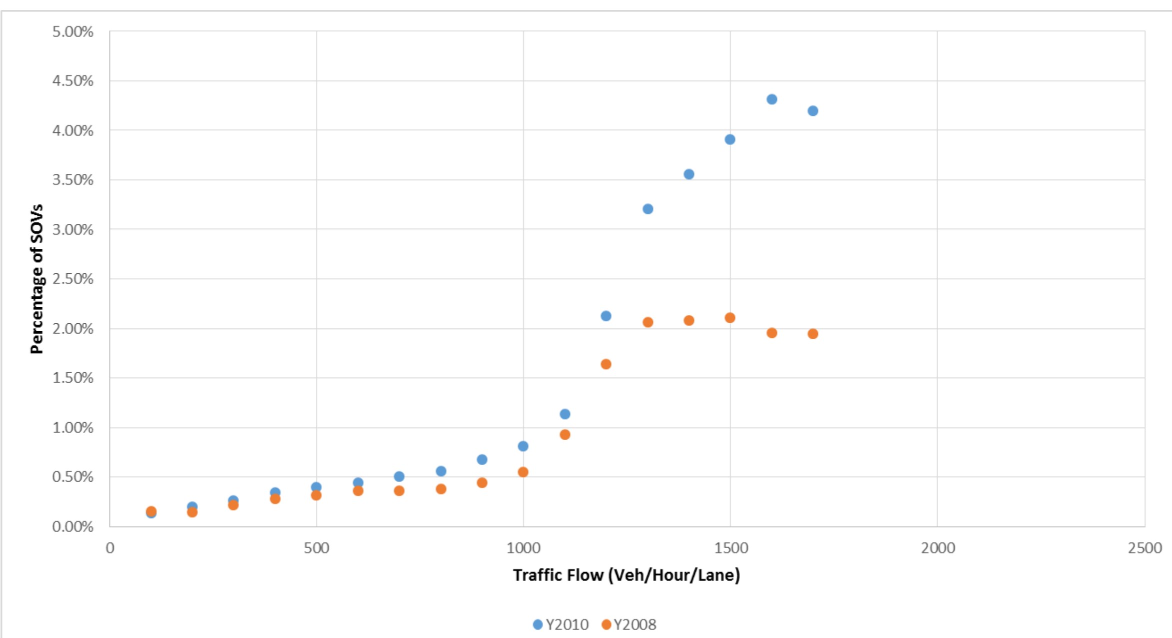

Figure 8 Percentage of SOVs in the HOT facility

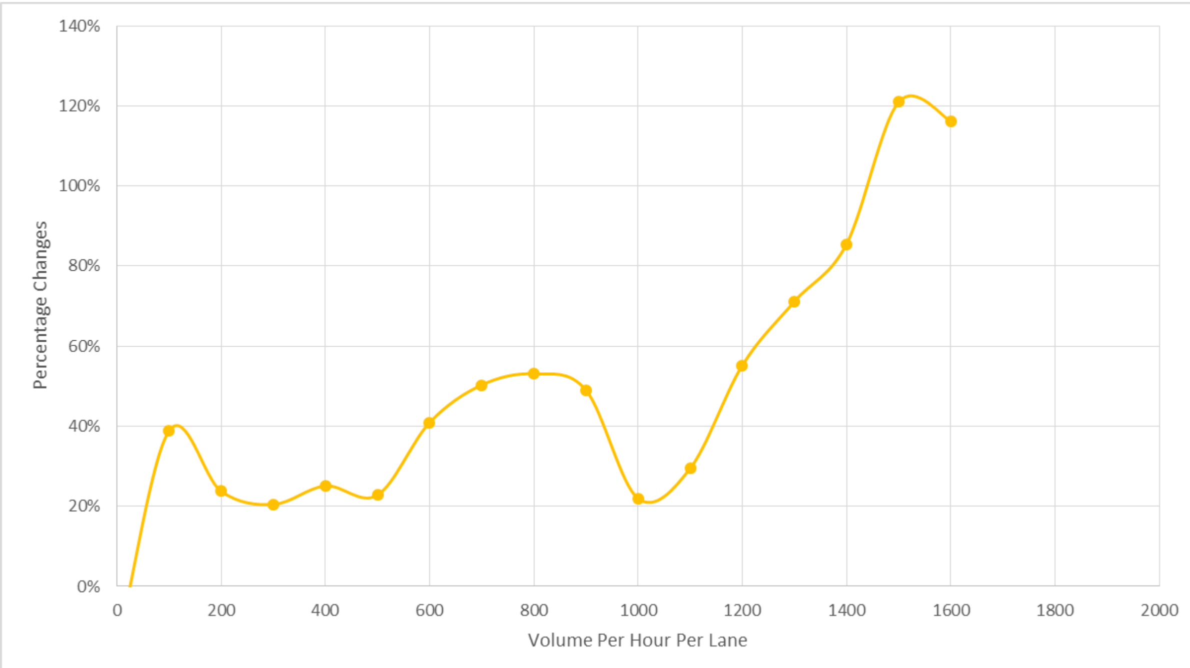

Figure 9 Percentage Changes from 2008 to 2010

Modeling the Percentage of SOV in the HOT Lane

Previous research found that travelers will likely to choose HOT lane even though the travel time saving is not significant or there is no travel time saving at all (Wood et al., 2014, Burris et al., 2012a). Therefore, factors other than travel time are included in the modeling. We used logistic regression models to evaluate the relationship between the probability for SOVs to select the HOT lane and several factors, including the traffic volume, toll rate, speed on general purpose lanes, and buffer index of speed on general purpose lanes, to identify the factors that affect drivers' choices and evaluate the importance of each factor. For exploratory analysis the percentage of vehicle paid toll in a time period i is calculated as

$$PercSOV_i = \frac{SOV_i}{SOV_i + HOV_i + VOL\_GP_i}$$

The data collected in this research do not include microscopic trip information, such as origin and destination, and aggregated average travel time. Instead, spot-detected speeds are available in both GP and HOT lanes. We define a Speed Buffer Index $SpdBI_i$ at time window i as

$$SpdBI_i = 90th\ percentile\ of\ speed_i - mean\ speed_i$$

The speed buffer index is similar to the travel time buffer index. It measures the range of variation of speed and is adopted as a measure of travel time reliability.

The mean values of the variables by year are show in Table 1. As can be seen, there is a 76% increase in average percentage of SOV users along with a modest 7% increase in traffic volume per lane. In consistency with the high increase in the percentage of SOV users, the HOV traffic volume increases 12%. Although the increased traffic volume has a minor impact on mean travel speed (1%~3% increase), the speed buffer index showed a substantial decrease of 22% and 10%. This result indicates that by converting HOV lane to a HOT lane, both GP and HOT lane have an improved travel time reliability. It also implies that speed variation and travel time reliability is more sensitive to traffic volume increase and potentially could affect users' decision on SOV use.

Table 1 Summary Statistics

Year	SOV Perc.	Traffic Volume (V/H/Lane)	GP Volume (V/H/Lane)	HOT VOL (V/H/Lane)	GP Speed	HOV speed	SpdBI_GP	SpdBI_HOT	Toll ($)
2008	0.69%	980	1269	403	57.2	54.8	0.54	0.30	0.70
2010	1.21%	1047	1344	452	58.8	55.9	0.42	0.27	0.64
% Changes	76%	7%	6%	12%	3%	1%	-22%	-10%	-8%

As stated before, the toll rates are dynamically correlated to traffic status and reversely the traffic condition will impact on the updated toll rates. To identify the inter correlations of the variables, multiple variables are compared pairwise. Comparing the coefficient between 2008 and 2010 indicated that the correlation with all the factors is generally much stronger in 2010 across board. This indicates a better acceptance of public of the HOT system and a more sensitive responses to the changes in these factors. The largest change is observed for the speed buffer index on general purpose lane "SpdBI'. The correlation between the SpdBI with the "SOV Perc" was 0.58 in 2008 and it increased to 0.72 in 2010. It shows that reliability is a key factor in decision making of SOV drivers who chose to pay in the HOT lane. The correlations of "SpdBI_HOT" and "Toll" with the percentage of SOV drivers are much higher in 2010 as well. This indicates a higher sensitivity of the public to traffic conditions in the HOT facility and users care more about the toll rates.

Error! Not a valid bookmark self-reference. and Table 3 also show that there are relative high correlation among factors, which prohibits the use of all factors in model-based analysis.

and **Error! Reference source not found.** show the correlations among variables for year 2008 and 2010. As can be seen from the results, the percentage of SOV users are highly correlated with overall traffic volume, traffic volume in general purpose lane and HOT lane, the speed on general purpose lane, and the speed buffer index on general purpose lane.

The toll rate is positively correlated with the percentage of SOV users (0.36 in 2008 and 0.56 in 2010). While seemingly counter intuitive, this is caused by the toll rate setting mechanism. The toll rate is dynamically updated based on the variation of demand. Therefore higher percentage of SOV user was generally associated with higher toll rate. The SOV user percentage is negatively associated with the speed on general purpose lane and HOV/SOV lane: the lower speed indicates a higher traffic volume and thus will promote the SOV lane usage. The higher speed buffer index indicates increased travel time uncertainly thus higher SOV lane usage, which implies that reliability is another critical factors in SOV usage. The correlation of percentage of SOV user with toll is among the lowest correlation values comparing to the other variables listed. Another interesting observation is that the correlation between "SpdBI_HOT" and the "SOV Perc" is much weaker than the case of "SpdBI", indicating that users were more sensitive to the traffic condition in the GP lane.

Comparing the coefficient between 2008 and 2010 indicated that the correlation with all the factors is generally much stronger in 2010 across board. This indicates a better acceptance of public of the HOT system and a more sensitive responses to the changes in these factors. The largest change is observed for the speed buffer index on general purpose lane "SpdBI'. The correlation between the SpdBI with the "SOV Perc" was 0.58 in 2008 and it increased to 0.72 in 2010. It shows that reliability is a key factor in decision making of SOV drivers who chose to pay in the HOT lane. The correlations of "SpdBI_HOT" and "Toll" with the percentage of SOV drivers are much higher in 2010 as well. This indicates a higher sensitivity of the public to traffic conditions in the HOT facility and users care more about the toll rates.

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Table 2 Correlation Table for 2008

	SOV Perc.	Traffic Volume	GP Volume	HOT Volume	GP speed	HOV speed	SpdBI	SpdBI _HOT	Toll
SOV Perc.	**1.00**	**0.55**	**0.45**	**0.70**	**-0.70**	**-0.33**	**0.58**	**0.23**	**0.36**
Traffic Volume	0.55	**1.00**	0.98	0.83	-0.62	-0.36	0.56	-0.13	0.35
GP Volume	0.45	0.98	**1.00**	0.70	-0.60	-0.34	0.54	-0.19	0.29
HOT Volume	0.70	0.83	0.70	**1.00**	-0.53	-0.33	0.49	0.09	0.44
GP speed	-0.70	-0.62	-0.60	-0.53	**1.00**	0.42	-0.85	-0.13	-0.38
HOV speed	-0.33	-0.36	-0.34	-0.33	0.42	**1.00**	-0.38	-0.49	-0.20
SpdBI	0.58	0.56	0.54	0.49	-0.85	-0.38	**1.00**	0.16	0.32
SpdBI_HOT	0.23	-0.13	-0.19	0.09	-0.13	-0.49	0.16	**1.00**	0.12
Toll	0.36	0.35	0.29	0.44	-0.38	-0.20	0.32	0.12	**1.00**

Table 3 Correlation Table for 2010

	SOV Perc.	Traffic Volume	GP Volume	HOT Volume	GP speed	HOV speed	SpdBI	SpdBI_ HOT	Toll
SOV Perc.	**1.00**	**0.51**	**0.39**	**0.70**	**-0.73**	**-0.33**	**0.72**	**0.27**	**0.56**
Traffic Volume	0.51	**1.00**	0.98	0.80	-0.51	-0.30	0.51	-0.11	0.36
GP Volume	0.39	0.98	1.00	0.65	-0.46	-0.27	0.45	-0.16	0.26
HOT Volume	0.70	0.80	0.65	1.00	-0.52	-0.30	0.57	0.08	0.56
GP speed	-0.73	-0.51	-0.46	-0.52	1.00	0.43	-0.89	-0.27	-0.40
HOV speed	-0.33	-0.30	-0.27	-0.30	0.43	1.00	-0.43	-0.58	-0.21
SpdBI	0.72	0.51	0.45	0.57	-0.89	-0.43	1.00	0.34	0.44
SpdBI_HOT	0.27	-0.11	-0.16	0.08	-0.27	-0.58	0.34	1.00	0.23

Toll	0.56	0.36	0.26	0.56	-0.40	-0.21	0.44	0.23	1.00

Regression Analysis

A logistic regression to model the relation between the probability of selecting SOV lane and other factors is developed. The model setup is as follows. Let Y_i be the number of vehicles selected SOV for time window i. We assume Y_i follows a binomial distribution:

$$Y_i \sim Binomial(N_i, P_i),$$

where N_i is the total number of vehicles in time window i; P_i is the probability of selection SOV lane.

We used a logit link function to link the probability of selecting SOV lane with the set of covariates:

$$logit(P_i) = \beta_0 + \beta_1 X_{1i} + \cdots + \beta_K X_{Ki}$$

where $\beta_0, \ldots, \beta_K$ are regression coefficient and $X_{i1}, \ldots, X_{Ki}$ are K covariates for time window i .

As indicated in the correlation analysis, there are strong correlations among variables. This will prevent them to be included simultaneously in the model because of multi-collinearity issue. Based on engineering judgement, we propose two sets covariates to be included in the models:

1) The first set includes overall traffic volume as measured by number of vehicles per hour per lane, toll rate, and the average speed in general purpose lane;
2) The second model includes overall traffic volume as measured by number of vehicles per hour per lane, toll rate, and speed buffer index.

Data from 2008 and 2010 are used to fit the model, respectively. The results are shown in Table 4 and Table 5. Based on the AIC values, both models provide insights into the influence of factor on HOT usage by SOV drivers. All the independent variables in both models are significant, except the toll in the models using 2008 data.

The results from 2008 indicated that overall traffic demand and the average speed on general purpose lane significantly impact the probability of SOV drivers to choose HOT lane. For model 1, increasing of the traffic volume and decreasing in average speed in the general purpose lane will increase the probability of choosing HOT lane. The toll rate, however, has no significantly impact on the probability though. For model 2, it can be seen that with the increase in speed buffer index, thus decrease in travel time reliability, SOV drivers are more likely to pay into the HOT facility. Similarly, traffic volume has positive impact on the probability while toll has very minimum impact on the results.

Table 4 Regression coefficient for 2008

		Estimate	Standard Error	z value	Pr(>|z|)
Model 1	**(Intercept)**	-2.85	0.69	-4.16	<0.001
	Traffic Volume (V/H/Lane)	0.14	0.03	5.15	<0.001
	Toll ($)	0.04	0.09	0.39	0.697
	General Purpose Lane Speed	-0.07	0.01	-7.85	<0.001
Model 2		**Estimate**	**Standard Error**	**z value**	**Pr(>|z|)**
	(Intercept)	-7.59	0.27	-28.51	<0.001

	Traffic Volume (V/H/Lane)	0.18	0.03	6.98	<0.001
	Toll ($)	0.11	0.09	1.26	0.209
	Speed Buffer Index in GP	0.83	0.13	6.31	<0.001

Comparing to 2008, the most noticeable change for the year of 2010 is that toll rate was statistically significant in both models. In addition, the magnitude of the point estimate for toll rate also increases substantially. All the other parameters are very similar to the case of 2008. This result implies that the traffic volume, speed, and the travel time reliability are still good indicators of the likelihood of SOV drivers who chose the HOT lane. Meanwhile, drivers are more responsive to the toll rate after the HOT facility in operation for 2 years. The parameters for tolls are both positive in the two models, which are compatible with the previous research that HOT users are not driven away by the tolls. Instead, they might use it as an indicator of upcoming congestion and decided to opt in.

Table 5 Logistic regression model output for 2010

		Estimate	**Standard Error**	**z value**	**Pr(>|z|)**
Model 1	**(Intercept)**	-2.85	0.44	-6.43	<0.001
	Traffic Volume (V/H/Lane)	0.14	0.02	7.77	<0.001
	Toll ($)	0.36	0.08	4.46	<0.001
	General Purpose Lane Speed	-0.06	0.01	-11.90	<0.001
Model 2		**Estimate**	**Standard Error**	**z value**	**Pr(>|z|)**
	(Intercept)	-6.93	0.21	-33.70	<0.001
	Traffic Volume (V/H/Lane)	0.15	0.02	8.11	<0.001
	Toll ($)	0.37	0.08	4.70	<0.001
	Speed Buffer Index in GP	0.88	0.08	11.57	<0.001

Conclusions and Discussions

HOT facility, a relatively new tolling facility, is where an existing HOV lane that used to be utilize by HOV vehicle only is converted to a high occupancy toll lane, e.g., HOV scan still use the facility for free while the single drivers will have to pay a toll to use the facility. The first HOT facility did not come in existence until 2001. This relatively innovative tolling scheme initiate a lot discussions and research interests in that:

1. The tolling is not a fixed value. Typically the toll rate updates every a few minutes according to the traffic condition. Traffic management authorities monitor the traffic condition in the HOT lane and set a goal to maintain by varying the toll rate. This goal can either be a free flow speed or a desired density. When the traffic gets congested and the speed or density measure exceeds the threshold, the toll rate will be raised to limit the usage of HOT lane by the SOVs. Therefore, the tolling rate is not only the reason but also the result of varied traffic condition. Under this circumstances, the mechanism behind the inter-correlation of traffic flow, toll rate, and willingness to pay is far more complicated.
2. The HOT facility usually runs side-by-side with the GP lanes. Access points are designed en-route to ensure easy in and out of the lanes. The chances for SOV drivers to decide whether to opt-in or opt-out of the HOT facility are continuously available along the road. SOV drivers can change their mind or/and make their decisions with their perceived traffic conditions on the road and the toll rate exhibited on the signing board. This flexibility further complicates the relationship of drivers' decisions, toll rates, and the traffic conditions.
3. As proved in previous research, the perceived travel time saving of travelers is not always true. Previous studies found that drivers might choose to pay for the HOT services even when the travel time saving is not significant at all, sometimes even with negative travel time savings.

In this project, the likelihood of SOV drivers to use a HOT lane is investigated using the data from SR 167 HOT facility in the year of 2008 and 2010. The goal of this research is to study how this the dynamic tolling system on HOT facility will affect driver's behavior. Two logit models using different dependent variables are fit for the data in 2008 and 2010. The results showed that:

1. The possibility of SOV drivers to choose HOT lanes is positively correlated to traffic volumes in GP lanes.
2. The possibility of choosing HOT lane has a negative correlation with the GP average speed, indicating that the slower the GP average speed, the higher the possibility that SOV drivers will buy their way into the HOT facility.
3. The possibility of choosing HOT lane has a much larger correlation with the speed reliability, illustrated using the speed buffer index, comparing to absolute speed measures. In fact, speed buffer index is the strongest explanation variable across the board.
4. The toll is not significant in the year of 2008 but significant in the year of 2010. This is a very interesting observation that confirms the ramp-up effects of toll facilities. Users' degree of acceptance was low in the opening year, where the toll rate will not affect SOV drivers' choices at all. After the HOT lane is in operation for 2 years, the drivers are getting more familiar with and are willing to pay.
5. The parameter for toll rate is positive and is significant for the year of 2010. It illustrates a positive relationship between the possibility of SOV drivers buy their ways into the HOT lane with the toll rates. This is not hard to understand because as stated before, the toll rate of HOT lane is a function of traffic flow and density. Drivers use the toll rate as an indicator after they

get familiar with the facility. A higher toll rate implicates an upcoming congestion and the SOV drivers responded by choosing the HOT lanes to avoid possible travel time fluctuations in the GP lanes.

As a preliminary study to study drivers' responses to the dynamic tolling system of HOT lane, this research has many potential future research directions:

1. It has been proved that driver's willingness to pay is not fixed. It usually will be affected by trip purposes and time of the trip. Also noticed is that the toll rate has a varied relationship with the percentage of SOVs willing to pay when the demand changes. Next the data can be categorized into peak and nonpeak time periods[2] or different demand levels to clarify the different effects the dependent variables on the probability SOVs choose the HOT lane.
2. Varied by the goals of the HOT facility, different parameters may play different roles. For example, the toll rate set may be different is the goal is to maximize throughputs versus to maximize revenue. The tolling scheming will be changed to fit the purpose the managing authority is looking for. Simulation models will be run to help designing tolling plan for the HOT lanes. For example, the data from the newly-opened beltway of Washington D.C. can be obtained and recommendations can be made through interpreting simulation results
3. Data from other locations can be collected and used for verifying the variations of model fittings. Because in previous researches it is found that income level in the area will affect the willingness to pay, it will be interesting to see how this variation will cause the model fittings.
4. The results show that drivers' reaction to tolls are dramatically different in the year of 2008 and 2010. This is a good hint for setting different tolling schemes for HOT facilities in the opening year and later on after the public gets more familiar with the facility. The results from this study can be further generalized to incorporate the ramp-up effects to provide insights and suggestions for management authority in their toll rate decision system.

[2] According to the report of "SR 167 HOT Lanes Pilot Project", morning peak hour is from 6-7 am and afternoon peak hour from 4-5pm.

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