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Procedia Social and Behavioral Sciences 16 (2011) 15–25

Procedia
Social and Behavioral Sciences

6th International Symposium on Highway Capacity and Quality of Service
Stockholm, Sweden June 28 – July 1, 2011

Measuring the Quality of Service for High Occupancy Toll Lanes Operations

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Abstract

High Occupancy Toll (HOT) lane systems have been proposed as one of the most applicable countermeasures against freeway congestion. Under HOT lane operational scheme, a Single Occupancy Vehicle (SOV) can pay to access HOT lanes in exchange of travel time saving or enhanced trip reliability when excess HOT lane capacity is available. Compared with regular freeway facilities, HOT lane systems demonstrate unique characteristics in facility capacity, driver behavior, travel pattern, demand modeling, and trip reliability. This study aims at conducting a comprehensive performance analysis on two representative HOT lane systems of State Route 167 in Washington and I-394 MnPass in Minnesota based on the field data collected from traffic sensors and transponder toll tags. Performance measurements are proposed to quantify the quality of service for HOT lane operations. Three critical issues are addressed in this study: 1) the speed-flow relationships in HOT lane systems, 2) quantified system-wide travel time savings and travel time reliability achieved, 3) SOVs tolling incentives. Based on the empirical analysis and evaluation results for the SR 167 and I-394 MnPass HOT lane systems, operational problems and challenges are also identified. Although the HOT lane system preserves favorable travel reliability, under-utilized HOT lane capacities were observed. The existing tolling strategies may be modified for better SOV allocation for HOT lane usages and further optimize the overall HOT system operations. The research findings greatly advance our understanding on HOT lane system operation mechanisms and are complementary to the freeway facility performance analysis provided by Highway Capacity Manual 2000.

Keywords: High-Occupancy Toll (HOT); Performance Measreument; Travel Time Reliability; Single Occupancy Vehicle (SOV); and Quality of Service.

1. Introduction

Fighting network-wide traffic congestion has been a major task for both federal and state transportation agencies over the past decades. The focuses of this work have been shifting from infrastructure expansions to efficient utilizations of existing facilities for congestion mitigation and sustainable traffic system developments. One of the new concepts being widely accepted is to combine congestion pricing and vehicle eligibility to maintain free-flow conditions on certain lanes while still providing a travel time saving incentive for high-occupant vehicles (HOVs). This scheme is often referred to as High Occupancy Toll (HOT) lane system which allows just enough additional traffic into underused carpool lanes. An electronic toll that fluctuates with the level of congestion lets solo drivers

doi:10.1016/j.sbspro.2011.04.425

use carpool lanes. The dynamic pricing keeps the HOT lane free flowing while reducing congestion in the adjacent General Purpose (GP) lanes.

HOT lanes are normally converted from previously underutilized HOV lanes operating concurrently with GP lanes and are separated from GP lanes by painted striping, buffer, or plastic pylons. In this scheme, a set of tolled lanes on an otherwise free and congested road offers high-quality service to people who are willing to pay a time-varying toll and/or who ride in carpools. There are ten HOT facilities in operation to date (University of Washington, 2009), including I-10 and US 290 in Houston, Texas, I-394 MnPass in Minneapolis, Minnesota, I-95 in Miami, Florida, I-15 in San Diego, California, SR 91 in Orange County, California, SR 167 in Seattle, Washington, I-25 in Denver, Colorado, and I-15 in Salt Lake City, Utah.

With HOT lane systems gaining more and more popularity, the performance measurements of these projects have emerged as a critical issue. A performance measurement platform has yet been established for the analysis of HOT lanes. For more than 35 years, the Highway Capacity Manual (HCM) has served as the guideline for defining quality of service of traffic facilities (Catbagan and Nakamura, 2006). However, the existing performance evaluation procedures included in HCM 2000 may not be directly applicable for HOT lanes because their unique features distinct from GP lanes, such as (1) a HOT lane may limit its access and exit points to specific locations only; (2) significant speed differences typically exist between a HOT lane and its adjacent GP lane; and (3) there are no opportunities for passing on single HOT lane facilities (Wang, Rouphail, and Zhang, 2008). All these unique operational HOT lane characteristics require the further studies on finding suitable measurements to better describe and quantify the HOT lane performance.

2. State of the practice

Unlike HOV lanes, HOT lanes can achieve a revenue generation where a toll is charged to Single Occupancy Vehicles (SOVs). SOVs can use the HOT lanes during peak-hour periods and avoid peak-hour highway congestion by paying a toll. SOVs are also encouraged to alter trip times to take advantage of lesser tolls during the shoulders of the peak periods (i.e., peak spreading) (Carson, 2005).

The HOT lane projects that are in operation offer unique opportunities to conduct system performance analysis and behavioural parameter estimation of drivers' preferences. However, because of their first-of-its-kind characteristics and relatively short periods since operation, most of the evaluations on HOT lane systems have focused either on the before/after analysis of HOT lanes' impacts on daily throughput, speed, and travel time (DeCorla-Souza, 2002) or on the attitudes, perceptions and reported travel behavior of commuters through survey.

Among several earliest implemented HOT lane projects, San Diego's FasTrak HOT lane program was open to public in 1999. To track the effects of this pricing structure evolution, a comprehensive monitoring and evaluation study was conducted by Supernak, et al. (2003) to investigate the use of value pricing as an instrument for better utilizations of the HOT lanes along the I-15 corridor. The study introduced two measures: peak period utilization factor (PPUF) and peak period distribution factor (PPDF) to investigate the impact of HOT lane on the travel patterns. It is concluded that LOS C was maintained virtually at all times during the study periods in 1997, 1998, and 1999. In the second study, Supernak et al. (2003) investigated the impacts of value pricing on this corridor with respect to travel time and travel time reliability. In general, the authors observed significant year-to-year changes in travel times along the I-15 general purpose lanes. Free-flow travel conditions were maintained at nearly all times. Results of the ramp delay study showed that, in the worst-case scenario, I-15 Express lane users can save up to 20 minutes per trip, avoiding approximately 4 and 16 minutes of delay on the I-15 GP lanes and on the ramp to the mainlanes, respectively.

There are also several technical evaluations and attitudinal studies of the I-394 MnPass HOT lanes in Minneapolis, MN. Zmud et al. (2007) analyzed the public's perceptions regarding the I-394 MnPASS system, and concluded that the willingness to pay for using the HOT lane was related to several factors, including income, age, trip purpose, time of day, trip distance, and amount of time saved. Cambridge, Inc. (2006) used performance data to evaluate performance impacts of I-394 MnPASS system, and it was found that the peak-hour throughput in HOT lanes increased by up to 5 percent and the speeds in both the HOT lane and the GP lanes experienced a slight increase.

3. Critical issues to be addressed

HOT lanes have become more prevalent on freeway facilities and research shows that they have been accepted by the public (Brownstone Small, 2005). There is an urgent need to better understand the operational characteristics of HOT lanes through analyzing the field observed data. However, widely accepeted methodologies for HOT lanes have not been developed so far, and performance measurement platforms are yet established. In our study, the research is being conducted with the ultimate goal of defining capacity and level-of-service (LOS) thresholds for HOT lane syste. Based on operational data collected under NCHRP project 3-96, Analysis of Managed Lanes on Freeway Facilities, this paper explores possible HOT lane performance measures using SR 167 HOT lane system in Seattle, Washington and MnPass I-394 in Minneapolis, Minnesota as a case study and advances the understanding of HOT lane system operation mechanisms.

This paper summarizes an empirical study of the HOT system's effectiveness, based on peak-hour period traffic data from loop detectors over four months and toll tag data over two months. Meaningful performance measures are identified and re-evaluated for assessing HOT lane perforamnce. The study addresses the following aspects:

(1) Speed-flow relationships in the HOT lane systems;
(2) Travel time saving and travel time reliability on HOT lanes; and
(3) SOVs' tolling incentives.

4. Study facilities and sites

The database for NCHRP 3-96 consists of nine HOV/HOT facilities in different regions of the country. The data collection sites encompass a combination of multiple configurations in terms of separation types, access points, number of lanes, operational strategies, etc. This study chose two HOT facilities from the database with similar design in separation types, access points and tolling strategies to analyze their operational performance. The details on each site are given below.

4.1 SR 167 in Seattle, Washington

The SR 167 HOT lane system is the very first and only HOT lane project in Washington State. It was open to public in May 2008. By converting the pre-existing HOV lanes into HOT lanes, SR 167 now allows solo drivers to pay for using the "express lane" previously reserved for carpools and buses.

The single HOT lane facility runs concurrently with the parallel two GP lanes for 10.76 miles northbound and 7.69 miles southbound between Renton and Auburn, Washington. Carpools, buses, and motorcycles continue to use the HOT lane free of charge. HOT lanes operate daily from 5 a.m. to 7 p.m. Toll rates are adjusted with the level of congestion. The toll varies as often as every 5 minutes, and is targeted to explicitly maintain a free-flow condition in the HOT lanes. Therefore, the adjustment of the tolling is to guarantee a travel-time saving and an improved travel reliability in HOT lanes (WSDOT, 2009).

The SR 167 HOT lanes pilot project divides the whole corridor into six segments northbound and four segments southbound with a weaving area between two consecutive segments called an access point. A double white line buffer separates the HOT lane from the GP lanes, which is illegal to cross. At the weaving area, the buffer becomes dashed lines, which indicates that you can freely enter or exit the HOT lane. At each access point, an overhead sign is installed to display the current toll rate. The toll rate can change at any time, but an SOV pays only the rate at the time it entered the HOT lane. An illustration of the access point is shown in Figure 1.

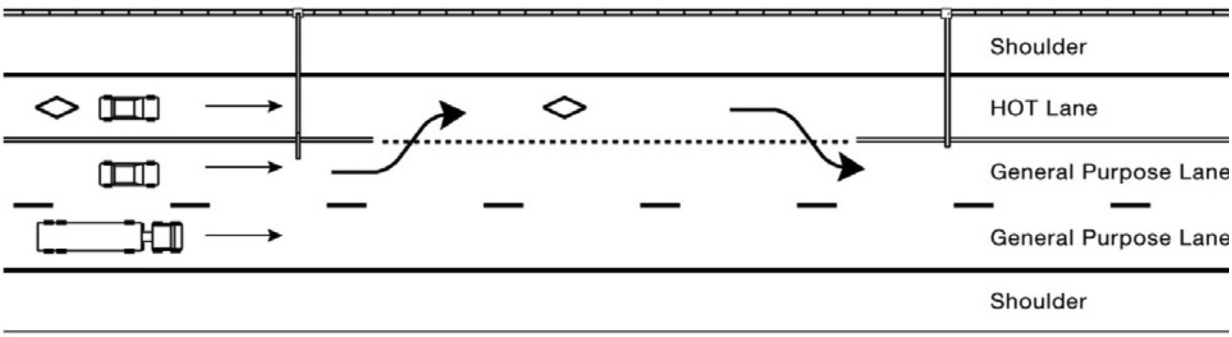


Figure 1: Access Point Design of SR 167

4.2 I-394 MnPass in Minneapolis, Minnesota

The I-394 MnPass HOT lane system has opened to public in Minnesota since May, 2005. SOVs who want to use the HOT lane will be charged a toll upon entry. The toll rate is changed in real time according to the congestion level. This 11-mile corridor is operating in the east/west direction and is serving traffic between downtown Minneapolis and the western suburbs. The whole facility is divided into two parts: a buffer-separated single HOT lane in the east and west directions of Hwy 100 (eastbound operating 6 a.m. to 10 a.m., and westbound operating 2 p.m. to 7 p.m.), and a reversible two-lane section east of Hwy 100 to downtown Minneapolis (Operating eastbound from 6 a.m. to 1 p.m. and westbound from 2 p.m. to 5 a.m.). The buffer-separated section shares similar design in all aspects with the SR 167's case, except with three GP lanes running parallel to the single HOT lane.

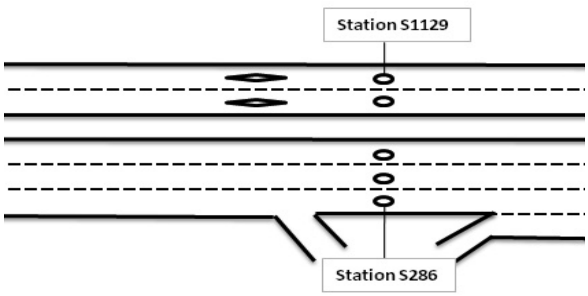
4.3 Field data collection

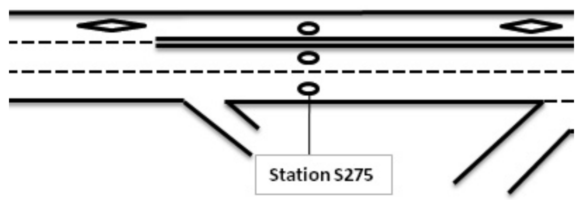
The data used in this study can be categorized into twofold: loop data and toll tag data. For the I-394 MnPass site, historical loop data covering four-month period (May to August, 2009) were obtained from the Minnesota Department of Transportation (MNDOT) at selected locations on I-394 MnPass. Both traffic volume and speed were recorded for each lane in 5-min intervals over the duration of the 5-hour/day (morning peak period). For the SR 167 HOT lane site, there are a total of 26 loop detector stations deployed along the corridor. Traffic counts and speed data are aggregated at 1-min interval and archived at the Traffic System Management Center (TSMC) of the Washington State Department of Transportation (WSDOT). Solo drivers who wish to use the SR 167 HOT lanes must subscribe to "*Good To Go!*" accounts and obtain transponders. A transponder serves as an electronic ID that maps toll transactions to a specific "*Good to Go!*" account. A transponder reader records transponders at their entrances to the HOT lane system and charge the mapped accounts based on the toll at the time of entrances. By matching the transponder IDs at the HOT lane access points, the Origin and Destination (OD) of each SOV traveling on the HOT lane and its travel time can be collected. Then the total travel time savings of vehicles using HOT lane over the GP lanes can be calculated. The loop data and transponder data were collected from the NB SR 167 during the morning peak period from 5:00 A.M. to 10:00 A.M. In total, a large amount of transponder data of 21 days was obtained from the site from February to March, 2009 for SOV's tolling incentives analysis. All the data were reviewed in detail and the erroneous detector readings were screened out.

5. Methodology

5.1 Speed-flow relationship analysis

The speed-flow curve determined by the HCM 200 for quantifying the performance of basic segments on freeways divides curve into two parts: the constant-speed portion and the unstable portion. It would be equally important to investigate the speed-flow curve of the HOT lane facilities and determine whether there is a difference between HOT and GP lanes' basic segments. Taking into account that the HOT lane is running parallel to the GP lanes, the drivers in the HOT lane can readily observe the traffic on the adjacent GP lanes, and feel uncomfortable passing congested GP traffic at a high speed differential without adequate separation. Therefore, the GP lane may impose an adverse effect on the HOT lane operation that draws the vehicles on the HOT lane to slow down. This effect is defined as "frictional effect" between the HOT and GP lanes, and the detailed discussion of this relationship is presented in Liu et al (2011). Considering this difference, we examined the speed-flow relationship from the MnPass I-394 HOT lane facility. Two locations are selected from this facility: Site A is located on the reversible 2-lane HOT lane portion, where a concrete barrier separates the HOT lanes from the GP lanes. Site B is located in the buffer-separated single-lane HOT section, where a two-foot buffer (double solid white line) separates the HOT lane from the adjacent GP lanes. The configuration of Sites A and C are shown in Figure 2. The selected locations are at least 1500 ft away from any on- or off- ramps in accordance with Highway Capacity Manual Definition (HCM, 2000).





Site A: I-394 EB @ Penn Avenue (Concrete Barrier Separated Two-lane HOT)	**Site B: I-394 EB @ General Mills (Buffer Separated Single-lane HOT)**

Figure 2: Schematics of Site Configurations (not to scale)

By plotting the speed-flow curves of HOT lanes and GP lanes at the same location, it is readily to observe the difference in operations. Note that tolling is dynamically managing the demand on HOT lane facilities to prevent breakdown, therefore, HOT lanes are expected to seldom experience breakdown for no matter how congested the adjacent GP lanes are.

5.2 Travel time saving and travel time reliability

Many transportation authorities are beginning to define more sophisticated measures for measuring congestion/mobility performance but have not yet implemented them. Overall, there appears to be a trend away from the general categories of performance (LOS) and toward continuous measures that are based on delay and travel time *(16)*. Further, travel time reliability is attracted more attention as another critical performance measure. However, its applicability is still questionable because of data availability and reliability limitations. Travel time can be measured in two ways. One method uses existing point traffic sensors to measure speed and then estimate travel time. The other solution is to directly collect travel time from transponder-equipped vehicles by matching transponder identification numbers at two points. In this study, travel time is obtained based on both methods. For travel time comparisons on both GP lanes and HOT lanes, the calculated travel time is used because there is no way to get transponder data for GP lanes. When analyzing the travel time reliability on HOT lanes, the transponder data is applied due to its capability of capturing the detailed variations in the HOT lanes' travel time. The SR 167 HOT lane northbound data are used in this analysis.

5.3 SOVs' tolling incentives

There has been extensive research related to tolling on HOT lane systems. Previous research ascertained that SOVs' decisions to use the HOT lane is not only related to the toll rate at the time they make the decision, but also related to some observed conditions such as traffic volume, speed, and their assumptions of travel time distribution on both the GP lane and HOT lane, and VOT, etc. (Zhang et al., 2008). This section focuses on evaluation of the SOV tolling incentives of the HOT lane system.

It is believed that for different types of users, their incentives of using HOT lane vary as well. The users in this study, based on the frequency of transponder IDs shown up in the database, are classified into two groups: frequent users vs. infrequent users. For the frequent users, they are more likely to use the HOT lanes even when there is no apparent benefit in travel time saving. They would rather buy in to use the lanes for reliability of the trip regardless of any indication of congestion downstream. For infrequent users, they value the immediate visible travel time savings more than trip reliability. Hence, their choices are more sensitive to the relative difference in traffic conditions between the HOT and GP lanes. It is assumed that under different traffic conditions, SOVs would react differently to tolling. Therefore, the traffic condition is classified into three different phases: pre-congestion, congestion period, and post congestion.

We modelled SOVs' lane choice decisions between two alternatives (GP vs. HOT lanes) in an actual market setting. To quantify the attractiveness of these two alternatives, the utility functions are defined to represent SOVs preferences, which are written as:

$$U_{HOT} = \alpha * TT_{HOT} + \omega * R_{HOT} + \beta * TR \tag{1}$$

$$U_{GP} = \alpha * TT_{GP} + \omega * R_{GP} + C \tag{2}$$

where TT and R stand for travel time and trip reliability, respectively. They are generic attributes which will impact the utilities of different lane types in the same way. *TR* is the HOT-specific attribute (toll rate) and *C* is the constant.

The details of the modelling procedure are demonstrated in Liu et al. (2011). One thing worth mentioning is that, for the trip reliability, we used a probability-based approach to measure the travel time reliability on both HOT and GP lanes. It is defined as the probability that a trip can be made successfully within a specified interval of time. Assume that for a study period, the travel time at a specific time of day follows a normal distribution, with mean and standard deviation of the distribution determined by historical data during each time period of day. The travel time reliability is expressed as:

$$Reliability = \Pr(t < t_{r_i}) = 1 - \Pr(t > t_{r_i}) \tag{3}$$

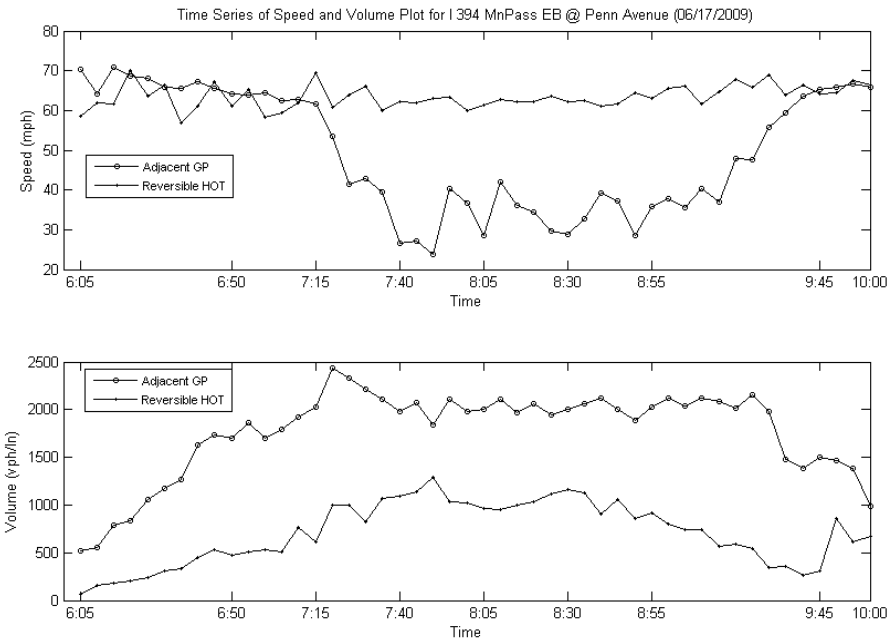
where t is the actual travel time for a given time of day; and t_{ri} is the required travel time for a given time of day.

This reliability measure converts the reliability into a scale of 0-1, where 1 indicates the most reliable conditions, 0 means the least reliable conditions. It is also noted that all travel times used in this study are estimated with the Piecewise Linear Speed Based (PLSB) model (Van Lint andVan Der Zijpp, 2003). This PLSB method reconstructs the mean travel times based on time series of speed measurement on consecutive detector locations. This method is proved to be almost unbiased given dense enough detector spacing (Tu et al., 2005).

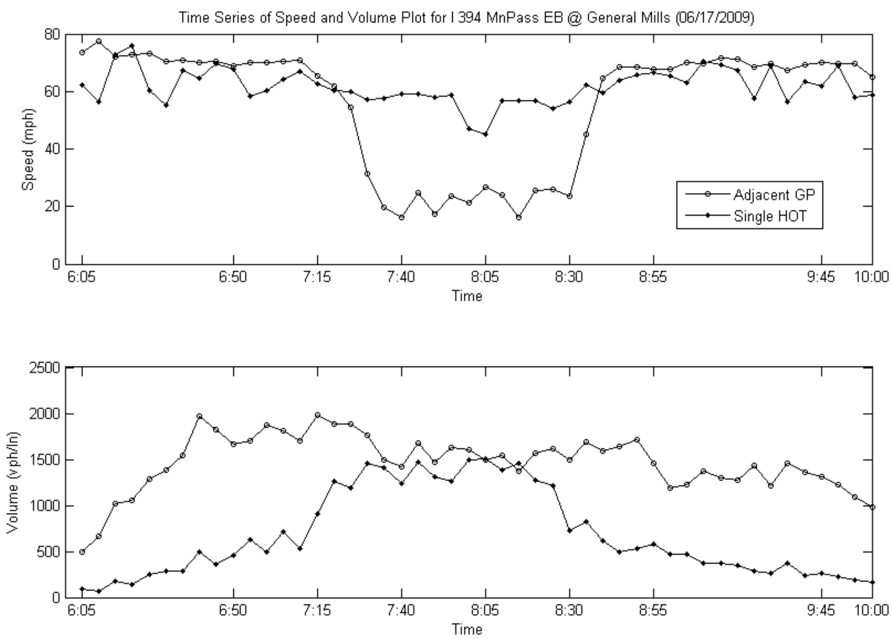
6. Results

6.1 Speed-flow relationship

Before analyzing the speed-flow relationship, the time series plots of speed/flow on both GP and HOT lanes are demonstrated to illustrate the HOT lane flow variations. In Figure 3 (a), before 7:30 A.M., the average speed across the GP lanes is relatively high, maintaining at 60 mph. However at 7:30 A.M., it is experiencing a sharp speed drop to below 50 mph, and generally remains below that threshold until 9:30 AM. During that congested period, the speed of the dual HOT lanes is maintained at non-breakdown levels. By looking at the corresponding time series volume plot, it is easy to identify that as the GP lanes are experiencing traffic breakdown, more people opt to pay to use the HOT lane to avoid the congestion. However, tolling is playing a key role during that period to dynamically manage the demand, so the HOT lanes can help alleviate a part of GP lane traffic by directing those paid customers to use the "express road". The same story holds true for Site B (Figure 3 (b)). However, we do observe a more severe speed drop to around 45 mph at 8:00 A.M. Recall that Site B is a single HOT lane running adjacent to the GP lanes with the buffer separation. Therefore, a more severe frictional effect may be imposed from the GP lanes that results in the speed reduction on HOT lane.



(a) Time series of speed and flow plots for Site A

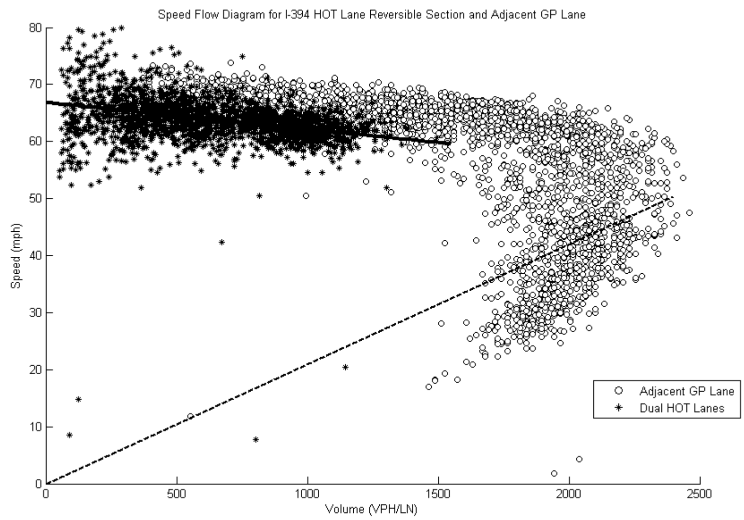


(b) Time series of speed and flow plots for Site B

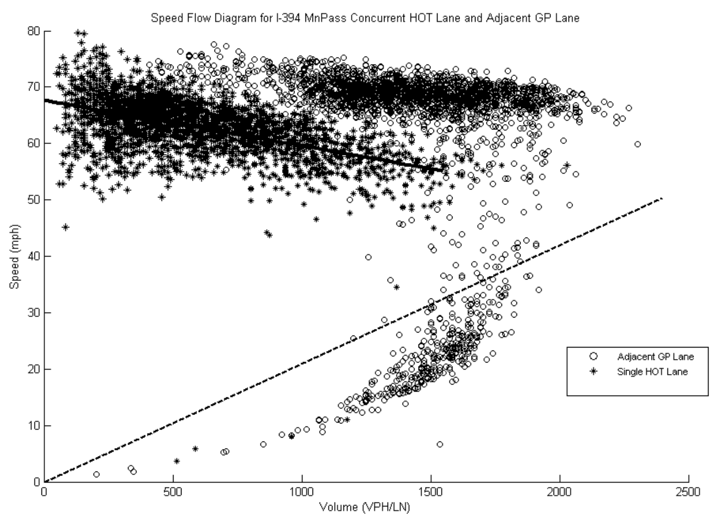
Figure 3: Time Series of Speed and Flow Plots for Site A and B

Figure 4 shows the speed-flow diagrams at the two HOT lane locations (Site A and B). Following the HCM basic freeway methodology (HCM, 2000), a reference line for the density at capacity of 45 passenger cars per mile per lane (pc/mi/ln) is added to both the diagrams. Because tolling adjusts the demand in the HOT lanes, it is expected that HOT lanes maintain stable flow conditions, and that breakdown conditions are prevented. This is validated from the field data collected, where only the stable portion of the speed-flow curve are observed for the

HOT lane. The speed-flow relationships suggest that, comparing with GP lanes', the HOT lane sites seem to drop more rapidly than what the HCM method would predict. This hypothesis is confirmed by using linear regression to estimate the slope of the HOT lane speed-flow data for Sites A and B as marked by the black lines in Figure 4. The resulting slopes of the regression lines are -0.0046 and -0.0080, respectively. Correspondingly, the slope of the observed single-lane site is approximately twice as steep as the two-lane locations. This finding is as hypothesized for single HOT lane facilities, where the impact of a few slow-moving vehicles more quickly impacts the general operations. In the context of this discussion it is further important to emphasize that GP basic freeway segments in the HCM 2000 have a constant speed (zero slope) up to a flow rate of 1200 passenger cars per hour per lane. The HOT lane data therefore suggest a speed drop of 0.4 to 0.8 mph for every 100-vehicle increase in flow rate. At the HCM 2000 breakpoint, this corresponds to an observed difference in speed of 4.8 to 9.6mph.



(a) Speed-Flow Diagram for Site A



(b) Speed-Flow Diagram for Site B

Figure 4 Speed-Flow Diagram for Site A and B

6.2 Travel Time Saving and Travel Time Reliability

Figure 5 demonstrates the travel times computed indirectly from the point traffic sensors through the SR 167 northbound corridor for Feburary, 2009. The figure also displays the median, 25th and 75th quartiles of travel time along the GP lanes as a function of departure times. The northbound free-flow peak-hour travel time in the HOT lane is 10.9 minutes, with a 95th percentile travel time of 11.1 minutes. The small difference between the two travel times in HOT lane indicates that speeds were successfully maintained, even during some of the most congested days. At 7:35 AM, the median value is 19.4 min for GP lane, which implies a maximum savings of 8.5 minutes. The maximum difference between the 75th quartiles and the median is 2.7 minutes, whereas the difference between the 25th quartiles and the median is 2.4 minutes.

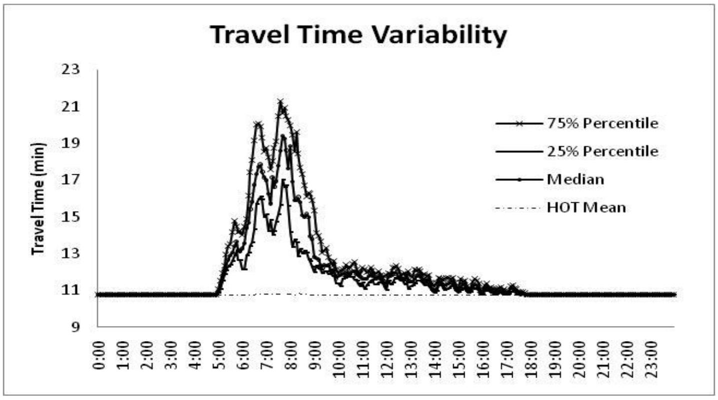


Figure 5 Travel Time Variability on SR 167 Northbound, February, 2009 (Days=Tu, We, Th)

There is growing recognition that not only does congestion occur on typical or average days, but also it is the variability which determines the trip reliability. Therefore, freeway performance must include the notion of reliability to both engineers and planners. In order to validate the travel time reliability on HOT lanes, the second method of measuring travel time was implemented, by matching the transponder ID with its according timestamp when SOVs enter each segment in SR 167 HOT lane. By finding the same tag ID at the entrance of each segment, the travel time of that segment for each specific SOV can be recorded. Figure 6 displays the dot diagram of average travel time that were extracted from the transponder reader's timestamp and aggregated into a 5-min interval for February and March, 2009. The reason that the travel time of segment 1 to 5 is displayed instead of segment 1 to 6 is that, the transponder reader can only record the tag ID at the entrance of each segment. Hence, the end time at segment 6, the last segment of the northbound corridor, cannot be recorded. The SOVs that had an OD from segment 1 to segment 6 were selected to analyze the corridor's travel time reliability. The time series plot in Figure 6 demonstrates the average travel time of those vehicles within these two months at different times of a day. The HOT lane maintains a steady travel time for the users with a mean value of 8.5 minutes, and a standard deviation of 26 seconds.

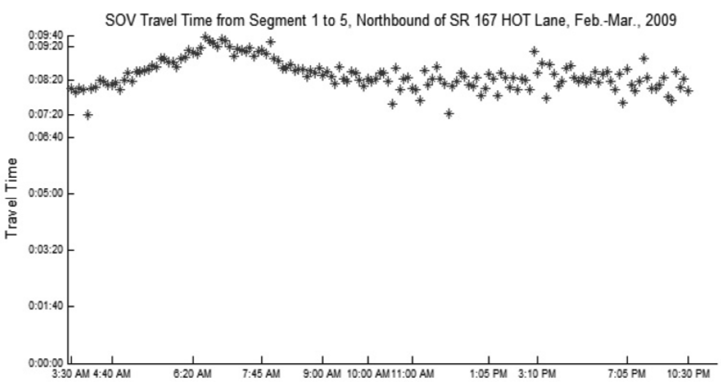


Figure 6 Travel Time Extracted From Transponder Reader for SR 167 Northbound, Feb.-Mar., 2009

6.3 SOVs' Tolling Incentives

To model SOVs' responses to the HOT lane operations, the data of morning peak period from SR 167 Northbound were collected and the whole period was categorized into three traffic phases: pre-congestion period (5:00 A.M. to 6:25 A.M.), congested period (6:30 A.M. to 8:30 A.M.) and post-congestion period (8:35 A.M to 10:00 A.M.).

All the models in the three phases yield a reasonable estimation result, with R square value ranges from 0.6 to 0.8. The detailed statistic results were presented in Liu et al, 2011. The toll rate in Phase 1 and 3, and the reliability in Phase 2 are not significant at 95% confidence level, therefore, they are eliminated from the final model. The final utility functions for the three traffic phases can be therefore written as:

Pre-Congestion:

$$U_{HOT} = -0.012 * TT_{HOT} + 1.042 * R_{HOT}$$
$$U_{GP} = -0.012 * TT_{GP} + 1.042 * R_{GP} + 2.511 \tag{4}$$

Congestion Period:

$$U_{HOT} = -0.214 * TR - 0.005 * TT_{HOT}$$
$$U_{GP} = -0.005 * TT_{GP} + 2.78 \tag{5}$$

Post-Congestion:

$$U_{HOT} = -0.003 * TT_{HOT} + 1.030 * R_{HOT}$$
$$U_{GP} = -0.003 * TT_{GP} + 1.030 * R_{HOT} + 3.338 \tag{6}$$

It is verified from the models above, that for different traffic phases, the SOV allocation is adjusted based on different user concerns. For the pre- and post-congestion period, SOVs care more about travel time saving and travel time reliability, which play a significant role in the models. This is reasonable because for those two periods, the toll rate is normally fluctuating between $0.5 and $1. Due to this relatively lower rate, the lane choice may not be determined by the fee, rather by a travel time saving and a reliable trip. During congestion period, however, toll rate is having a significant impact on the SOV demand. During that period, the SOV demand in the HOT lane would increases as the toll rate goes up. This seems counterintuitive at first glance, but is explainable under the dynamic tolling context since it captures the signaling effect of the congestion pricing scheme. The toll is adjusting based on the real time volume and speed measurements on both HOT lane and GP lanes. Since SR 167 HOT lane virtually seldom experiences any congestion, the toll rate is functioning as a signal implying the traffic condition on both downstream HOT lane and GP lanes (normally fluctuating between $1.00 to $2.75). For the majority of HOT lane users, when the toll rate goes up during the congested hours, it indicates that the downstream traffic in the GP lane is fairly congested. Therefore, people would rather pay more to use the HOT lane to avoid the traffic. Also, it is noted that travel time is significant in all the three phases, indicating the fact that the priority for people choosing the HOT lane is for an immediate benefit of travel time saving.

7. Conclusion

The concept of HOT lane has been widely adopted as an effective countermeasure against freeway congestion. A lot of research has been conducted to examine how HOT lane can improve the overall throughput and alleviate congestion from transportation policy perspectives. However, few efforts have been performed to evaluate the performance measurements applied on HOT lane from an operational standpoint. This paper summarizes an empirical study of the HOT system's effectiveness, based on traffic data. Meaningful performance measures such as speed, volume, and travel time that are used for assessing the highway effectiveness are identified and re-revaluated for application to the HOT lane system. It is found that tolling is playing a key role to dynamically manage the demand and avoid the HOT lanes from reaching breakdown. By examining the speed-flow diagram from selected location, it is concluded that the stable part of HOT lane speed-flow diagram is not a horizontal line as HCM 2000 predicts. Instead it drops more rapidly due to the frictional effect from the GP lanes. Due to the observable friction effect, a congested GP lane would have an adverse effect on the adjacent HOT lanes, even when the HOT lanes themselves are operating below capacity. It is also found that the reviewed HOT facilities are not degraded while maintaining the "safety valve" function. The average speed on SR 167 HOT lane maintains at or above 45 mph during peak hour for 95% of the time. The average peak-hour travel time held steady at approximately 11 minutes northbound. From the SOVs' tolling incentive analysis, it suggests that, under different traffic conditions, the SOVs lane choices may be affected by different attributes. This is important in the consideration for an optimal tolling policy setting, which oftentimes overlooks users' concerns variation under different traffic phases. However, people do give a priority in immediate travel time saving in the entire peak period. The results of this research are important as analysts are developing methods to better understand the effectiveness of HOT lane performance. It is also important in the consideration for an analytical procedure for HOT lane performance evaluation in a Highway Capacity Context under NCHRP 3-96.

Acknowledgement

The authors acknowledge the support by NCHRP 03-96: Analysis of Managed lanes on Freeway Facilities research project. The authors also would like to thank Washington Department of Transportation (WSDOT) and the Minnesota Department of Transportation (MNDOT) for providing the loop detector data and transponder reader information.

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