2010 13th International IEEE
Annual Conference on Intelligent Transportation Systems
Madeira Island, Portugal, September 19-22, 2010



# Impacts of High Occupancy Toll Lane Operations on High Occupancy Vehicle Travelers

Guohui Zhang, Yao-Jan Wu, Xiaoyue Liu, and Yinhai Wang

**Abstract—Providing quality travel conditions to High Occupancy Vehicles (HOVs) is essential for travel demand control and High Occupancy Toll (HOT) lane system operations. In most HOT lane systems converted from previous HOV lane facilities, physical barriers or double white lines are utilized to separate HOT lane from General Purpose (GP) lanes. Only specified merging areas are available for both HOVs and Single Occupancy Vehicles (SOVs) to access or exit HOT lane. These spatial restrictions as well as the interruption of flow progression caused by the increased weaving movements may deteriorate HOV travel conditions. Quantitative analysis on HOVs travel condition under different traffic conditions is very important for understanding the HOT lane impact on HOV travel and for optimizing overall HOT lane system operations. This study concentrates on investigating HOV travel conditions in the HOT lane system with various HOV proportions under different traffic conditions. A simulation-based HOT lane operation analysis is conducted. A microscopic traffic simulation software tool, VISSIM, is utilized and an external module to enable dynamic HOT lane operations is developed. The Washington State Route (SR) 167 HOT lane system is simulated. The research findings indicate that under current traffic demands HOT lane system can improve overall HOV travel conditions due to the overall system performance enhancement. However, negative impacts of HOT lane systems on HOV travelers become significant with increased traffic demands. This study demonstrates quantitative impacts of HOT lane systems on HOV travelers and provides in-depth analysis for HOT lane performance evaluations.**

**Key words: High Occupancy Toll (HOT) lane, High Occupancy Vehicle (HOV), Performance Analysis, and HOT Lane Simulation.**

## I. Introduction

From 1980 to 2005, yearly Vehicle Miles Traveled (VMT) increased by 96%, while road mileage increased only about 4% nationally (1). The 2005 Urban Mobility Report indicates the annual delay per person was 47 hours and an average of $794 per traveler resulted from congestion in the 85 surveyed-urban areas in 2003 (2). In Seattle, traffic congestion resulted in a total of 72.46 million hours of travel delay and 49.22 million gallons of excess fuel consumption in 2003, corresponding to a congestion cost of 1.24 billion dollars, the 15th highest in the U.S. (2). Adding more roadways has been a traditional solution to solving traffic congestion problems. However, the increase in roadway supply has far lagged behind the increase in demand over the past several decades. It is of practical importance to manage and utilize the existing traffic facilities more efficiently when expanding highway capacities becomes more difficult in metropolitan areas.

High Occupancy Vehicle (HOV) lane system has been proposed to motivate people to shift from Single Occupancy Vehicles (SOVs) to carpools or buses in order to reduce SOV trips and ease traffic congestion (3). It has been widely recognized that HOV lanes can carry more people than General Purpose (GP) lanes during peak hours. Kim conducted a study using micro-simulation models and found HOV lanes improved travel time significantly (4). On the other hand, the research on the usage of HOV lanes conducted by Dahlgren indicates under some circumstances HOV lanes are less effective in reducing traffic delay (5). In Kwon and Varaiya's studies (6), HOV lanes were found to increase congestion in the Bay area HOV networks by underutilizing the lane capacities by about 20% or 400 vph. Many HOV facilities are underutilized when other GP lanes are congested. This may be partially because about 43% of carpoolers are members of the same household and exploitation of HOV lanes is restricted to some extent (7). Under such a background, converting HOV lane facilities to High Occupancy Toll (HOT) lane systems is considered to be an effective solution. SOVs are allowed to pay a toll for using HOV lanes and the excess capacities of HOV lanes can be better utilized. Currently, there are about 1285.3 miles of HOV lanes in the US (8). Successful operation of HOT lanes by fully exploiting their excess capacities will generate huge potential time savings and significantly mitigate traffic congestion. Therefore, HOT lanes have been increasingly recognized in research and practice as a viable measure to improve traffic operation efficiency.

The first HOT lane project was implemented on State Route 91 in Orange County, California in 1995. After that, other states, such as, Texas, Minnesota, Colorado, and Washington, have implemented HOT lanes (9). Although many studies have been conducted to empirically evaluate the system performance of these projects (10 ~ 17), few of them were dedicated to quantitatively analyzing the impacts of HOT lane systems on HOV travelers. Because one important control criterion of HOT lane systems is to

Manuscript received July 20, 2010.

Guohui Zhang is with the Center for Transportation Research at The University of Texas at Austin, Austin, TX, 78705 USA. (corresponding author). Phone: 512-785-2296; e-mail: guohui@mail.utexas.edu.

Yao-Jan Wu, is with University of Washington, Seattle WA 98105 USA. e-mail: yaojan@u.washington.edu.

Xiaoyue Liu, is with University of Washington, Seattle WA 98105 USA. e-mail: xyliu@u.washington.edu.

Yinhai Wang, is with University of Washington, Seattle WA 98105 USA. e-mail: yinhai@u.washington.edu.

978-1-4244-7659-6/10/$26.00 ©2010 IEEE

preserve high-quality travel condition and trip reliability for HOVs, in-depth investigations on HOV travel patterns is indispensable for better understanding the HOT lane system control mechanisms. This study concentrates on studying HOV travel conditions in HOT lane system with various HOV proportions under different traffic demands. A simulation model is established for the Washington State Route (SR) 167 HOT Lane Pilot Project using the microscopic traffic simulation software, VISSIM. Various experimental test scenarios are established to quantify HOT lane systems' impacts on HOV travel conditions. This paper is organized as follows. The next section briefly describes the state of the practice regarding the representative HOT lane systems. It is followed by an in-depth analysis of potential impacts of HOT lane systems on HOV travelers. Then the SR-167 HOT lane simulation model and the tolling strategy are briefly presented in Section 4. The experimental tests and results are detailed in Section 5. The final section concludes this research effort and proposes further research topics.

## II. STATE OF THE PRACTICE

In practice, HOT lane systems have been implemented in California (SR-91, and I-15), Texas (I-10 and US-290), Minnesota (I-394), Utah (I-15), Colorado (I-25), and Washington (SR-167). Others, such as Virginia, are currently planning to implement HOT lane projects (16). The representative HOT lane projects are described as follows.

The I-15 Express Lane system in San Diego is an eight-mile long barrier-separated HOT lane system. The tolls typically range from $0.50 to $4.00 according to the time of day and may be adjusted in response to real time traffic conditions. The maximum value of $8.00 is employed for heavily congested situations (17). The update interval is specified as six minutes to maintain free flow conditions. In 2004 and 2005, the average daily traffic volume carried by I-15 Express Lanes during weekdays ranged from 19,401 veh/day (in February 2005) to 22,341 veh/day (in March 2004), and HOVs accounted for approximately 75% to 78% of the total vehicles (18).

The I-394 MnPass lane system opened in Minnesota in 2005. The original HOV lanes are approximately 11 miles in length including two different sections: a three-mile, barrier-separated reversible section located to the west of downtown Minneapolis, and an eight-mile section of concurrent flow HOV lanes located to the west of the first section (20). A series of implementation activities were executed for the I-394 MnPass lanes including restriping the concurrent flow HOV lanes to change from unlimited to limited access, installing the electronic collection and enforcement systems, and so on. A similar pricing mechanism is implemented. The tolls are adjusted upward or downward to ensure the HOT lane flow rates at about 50-55 mph. The traffic density is applied as the detection input and the update interval for tolling is specified as 3 minutes. The toll ranges from 25 cents to $8 and averages $1 to $4 during rush hours (21). Traffic counts from mid-2006 recorded 1,756 vehicles using the concurrent flow HOT lane section in the morning peak hour, and HOVs accounted for about 63 percent (20).

The SR-167 HOT lane system has been in operation since May 2008. SR-167 is a primary highway connecting south King and north Pierce counties to the Seattle/Bellevue metropolitan area. It is also an important alternative route to Interstate 5 for moving both people and goods in the Puget Sound Region. There is one HOT lane and two GP lanes on each direction of the corridor. Restriping added a double-white line as a barrier to separate HOT and GP lanes. Crossing this double-white line is illegal. Nine-mile southbound and 12-mile northbound HOT lanes include several intermediate access points: three access points for the southbound lane, and four for the northbound lane, respectively (22). This HOT lane system uses flexible pricing technology and the toll will automatically adjust up or down to optimize the HOT lane volume and maintain its speed at 45 mph or higher. The toll varies from $ 0.50 to $ 9.00 based on the levels of service conditions on HOT and GP lanes (22). This SR-167 HOT lane system is one representative HOT lane project in the U.S. through converting a single HOV lane to a HOT lane with multiple access points.

## III. PROBLEM STATEMENT

The existing studies investigated these HOT lane system operations with emphases on overall system performance evaluations. Sufficient time savings and increased total throughputs were observed through better distributing traffic between the congested GP lanes and the previously underutilized HOV lanes. As one critical operational objective of HOT lane systems, an acceptable Level of Service (LOS) for HOVs should be preserved to ensure their travel reliability. However, few studies were conducted to quantify the impacts of HOT lane systems on HOV travelers. When existing HOV facilities were converted to HOT lane systems, such as the I-394 MnPass system and the SR-167 HOT lane system, a series of remodeling steps were taken. For instance, restriping lane marks to separate HOT lanes from GP lanes, and deploying restricted areas for vehicles accessing and exiting HOT lanes. Compared to unlimited access to HOV lanes, HOV operations may degrade to some extent in the HOT lane system due to spatial limitations on lane changing. Additionally, when tolled SOVs are allowed to use the HOT lane, increased weaving and merging movements may unfavorably interrupt flow progression and introduce unexpected delays for HOVs. On the other hand, HOV travel conditions can be improved due to overall system operation enhancement because when some SOVs are diverted to use HOT lanes, travel conditions on GP lanes are upgraded significantly. Investigations on potential impacts of HOT lane systems on HOV travelers in various HOV proportions under different traffic demands are highly desired to fully understand HOT lane operation mechanisms and develop optimal tolling strategies to encourage travelers to shift from driving alone to carpooling. However, such studies are constrained by the data availability and reliability in practical HOT lane systems. Traffic simulation provides a cost-effective and risk-free means of exploring and researching these issues. Hence, in this study, we are motivated to conduct comprehensive investigations and in-depth analyses on impacts of HOT lane systems on HOV travelers based on VISSIM simulation model calibrated by the Washington SR-167 HOT lane system.

## IV. HOT LANE SIMULATION MODEL DEVELOPMENT

The HOT lane simulation model is developed for the SR-167 HOT lane project. The details regarding the simulation model development, external module integration and model calibration can be found in the previous work (23). For the purpose of self-explanation, they are briefly described as follows.

### A. VISSIM External Module Development

In this study, the microscopic traffic simulation software, VISSIM 4.30, is utilized to investigate HOV operations for the SR-167 HOT lane system. Although VISSIM is widely utilized for freeway modeling due to its competent capabilities of simulating common transportation operations (24, 25), it cannot sufficiently handle the HOT lane operation issues using its built-in modules. In VISSIM, a static toll rate can be set up as the financial cost for each roadway segment, but it is not dynamically changeable to reflect changing traffic conditions. In the latest version, one HOT lane operation module is provided by VISSIM. However, it can only support the very simple tolling strategy by specifying a series of thresholds. In this study, an external HOT lane module is developed via VISSIM Component Object Model (COM) interfaces to enable dynamic HOT lane simulation. The feedback-based dynamic tolling algorithm is adopted. A second-order control scheme is exploited. Based on traffic speed conditions and toll changing patterns, the optimum flow ratio for HOT lane utilization is calculated using feedback control theory. Then the appropriate toll rate is estimated backward. The tolling algorithm development is detailed in the literature (26)

### B. SR-167 HOT Lane Simulation Model Development

To fully investigate and analyze impacts of HOT lane systems on HOV operations, a simulation model is established for the SR-167 HOT lane project. The detailed information regarding SR-167 HOT lane simulation model configuration and calibration is expressed in the previous work (23, and 26). To avoid description duplication, only crucial components for model development and calibration are presented as follows.

The simulation network is configured to exactly represent the roadway geometric features, including the location of on-ramps and off-ramps, horizontal and vertical curves, weaving sections, the number of lanes and so on. Three morning-peak hours, from 6:00am to 9:00am, is chosen as the simulation time period. This study concentrates on the HOT lane operations on Northbound SR-167. The traffic composition is represented by a number of vehicles from three categories: SOVs, HOVs and trucks. Based on their OD matrices established using the base-year traffic survey data, VISSIM can dynamically assign and equilibrate traffic in the network with its built-in dynamic assignment module. The original HOV lane operations and HOT lane operations are simulated. Five HOT segments are implemented following its exact geometric characteristics from SR-167 & 15$^{th}$ St. SW in Auburm to SR-167 & I405 Interchange Bridge in Renton. Virtual loop detectors are employed in the VISSIM model to match their real locations and real-time traffic simulation data can be read by this external HOT lane module via COM interfaces. In our study, the value of time of $11.7 per hour is applied in this project. This value was obtained from the traffic survey in the greater Seattle area.

The simulation model is calibrated carefully to ensure realistic representation of simulated scenarios and to achieve reliable simulation results. The details of the calibration process are introduced in the literature (23). The calibration results are validated by comparing simulated traffic volumes and speeds with ground-truth data at the check points including five important locations on the SR-167 corridor and two locations on the I-450 interchange bridge. Based on both volume and speed comparisons at several vital locations, we believe that the overall simulation outputs are reasonably consistent with the reference data. Therefore, we conclude that the model is well calibrated and can produce reliable analysis and results.

## V. EXPERIMENTAL TESTS AND RESULT DISCUSSIONS

Simulation experiments are conducted to quantify operation performance of HOVs in the HOT lane systems under a variety of traffic conditions. The loop data and survey studies indicate traffic composition consists of 6% trucks and 94% passenger cars, including 80% SOVs and 14% HOVs in the Seattle area, Washington (27). It is expected that HOT lane system implementations may induce increased traffic demands and attract more HOV travelers. Therefore, 16 test scenarios are designed with different HOV proportions under various traffic demands. Based on calibrated simulation model, the current traffic demands serve as the master data, then traffic volumes change in 10% increments from 100% to 130% of the current demands. Meanwhile, the proportion of HOVs varies from 10% to 25% of total traffic compositions at increments of 5%. Combining different traffic demands with diverse HOV proportions, wide-ranging test scenarios are generated to provide a reliable platform to investigate impacts of HOT lane systems on HOV travelers. To minimize the randomness of simulation results and enhance simulation models' credibility, multiple simulation runs are necessary. In this study, a total of 7 simulation runs were conducted, each with a different random seed arbitrarily selected for each scenario. The integrated results from these simulation runs are considered statistically reliable and unbiased.

First, simulation experiments were conducted with various HOV proportions under existing traffic conditions. The integrated simulation results of the 25% HOV proportion test scenario are summarized in Table 1, including travel time, throughputs, and space-mean speeds for both HOVs and total traffic. As we can see, slightly improved travel conditions for HOVs are achieved by HOT lane operations compared with HOV lane operations. For example, Lane Segment 4, which is 2.4-mile long with 2 on-ramps and 2 off-ramps, the average HOV speed for mainstream travel is about 56.5 MPH under HOV lane operations, which is slightly lower than the HOV speed, 58.0 MPH under HOT lane operations. For the on-ramp and off-ramp HOVs, the higher average speeds are observed by the HOT lane system because significant improvements on GP lanes are achieved by the HOT lane systems. However, due to the increased weaving movements in the merging area in the HOT lane system, the average HOV speed is about 54.0 MPH, which is lower than 59.3 MPH. Due to the short length of the merging area, such negative impacts would not be significant. The analysis for the total traffic indicates an improved travel condition when HOT lane systems are in operation. Therefore, the results show that under the current traffic demands, HOT lane system implementations can improve the HOV travel conditions along the mainstream corridor, on-ramp and off-ramp sections. When a certain proportion of SOVs are diverted to the HOT lane, the GP lane conditions are improved which enhance both SOV and HOV travel conditions. However, further analysis indicates the improvements of HOV travel conditions are not statistically significant as illustrated by the following results. Further simulation tests were conducted through broadly changing traffic demands and HOV proportions. Table 2 and 3 illustrates HOV speeds and throughputs on the HOT lane segment 4 for different test scenarios with the demands distributing from 100% to 130% of the current demand, and the HOV proportions ranging from 10% to 25%. To facilitate the comparison of HOV speeds and throughputs achieved under HOV lane operations against these under HOT lane operations, an improvement ratio is defined. The HOV speed difference between the HOT lane system and HOV lane system is divided by the corresponding speeds under the HOV lane system. Similarly, an analogous variable is defined for traffic throughputs. As we can see in most of the scenarios with the demands less than 130% of the current demands, slight improvements can be observed. For example, under 110% of the current demand with a 15% HOV proportion, the average HOV speeds are 57.7 MPH and 53.6 MPH for the mainstream and on-ramp sections under HOV lane operations. They slightly increase to 58.2 MPH and 54.4 MPH respectively under HOT lane operations. The on-ramp HOV speed maintains at the same level. When the traffic demand continues increasing to 130% of the current traffic demand, however, significant negative impacts on HOV travelers are observed. In Table 3, when the HOV proportion increases from 10% to 25%, the HOV travel conditions consistently deteriorate. The HOV speed drops from 11.49% to 26.4% for the mainstream section and from 5.64% to 49.03% for on-ramp and off-ramp section. This is because when the demand increases and exceeds the critical HOT lane system capability, the HOT lane system is overloaded. The HOT lane speed is about 50 MPH and the GP lane speed drops to 35 MPH or even lower. Under such conditions, the spatial constraints for HOT lane access and exit become severe to these HOVs taking on-ramps or off-ramps, and they have to travel on highly congested GP lanes for relatively long distances. For the mainstream HOV travelers, negative impacts from tolls SOVs are also apparent because additional weaving, merging and queuing movements caused by increased volumes.

## VI. CONCLUSIONS

In this study, VISSIM-based simulation models were developed to examine the HOV operation performance in the HOV lane and HOT lane systems. The SR-167 HOT lane system in Washington State was modeled, and five HOT lane sections on the northbound corridor were concentrated due to their diverse features. The simulation results show the traffic demand levels and system-wide congestion situations critically impact HOV travel conditions in the HOT lane systems. Under moderate congestion levels, slight improvements of HOV travel conditions can be achieved by the HOT lane system compared to HOV lane operations because of overall system operation enhancement. However, such improvements are not statistically significant. When the entire HOT lane system is highly congested, HOV travel conditions degrade considerably. Under such conditions, the spatial constraints for HOT lane access and exit because severe for these HOVs taking on-ramps or off-ramps, and they must travel on highly congested GP lanes for relatively long distances. For the mainstream HOV travelers, negative impacts from tolled SOVs are also apparent because of additional weaving, merging and queuing movements caused by increased volumes. Additionally, without considering traffic demand factors no consistent impact patterns are found for different HOV proportions. The dynamic tolling strategies can adjust toll rates to regulate the number of SOVs for HOT lane utilization and HOV volume changes can be accommodated.

**Table 1 Integrated Simulation Results of HOV Data with the various HOV Proportion under 100% and 110% of the Current Traffic Demands for HOT Lane Segment 4 From 7 Simulation Runs**

| Simulation Time Period: 6:00-9:00 Am | | | HOV Lane Operations | | | HOT Lane Operations | | | Improvement | |
|---|---|---|---|---|---|---|---|---|---|---|
| Traffic Demand | HOV Proportion | Roadway | TT[a] | TP[b] | SP[c] | TT[a] | TP[b] | SP[c] | TP[b] | SP[c] |
| 100% | 10% | Mainstream | 145.2 | 468 | 58.5 | 145.3 | 494 | 58.4 | 5.56% | -0.23% |
| | | On-Ramps | 77.9 | 358 | 54.9 | 78.9 | 357 | 54.1 | -0.28% | -1.39% |
| | | Off-Ramps | 70.2 | 228 | 49.3 | 72.4 | 243 | 47.7 | 6.58% | -3.13% |
| | 15% | Mainstream | 146.3 | 706 | 58.1 | 146.1 | 731 | 58.1 | 3.54% | -0.02% |
| | | On-Ramps | 78.6 | 540 | 54.5 | 77.5 | 542 | 55.2 | 0.37% | 1.29% |
| | | Off-Ramps | 69.7 | 349 | 48.1 | 69.4 | 375 | 48.3 | 7.45% | 0.46% |
| | 20% | Mainstream | 147.4 | 1007 | 57.7 | 146.4 | 1003 | 58.0 | -0.40% | 0.52% |
| | | On-Ramps | 79.0 | 714 | 54.2 | 76.6 | 719 | 55.8 | 0.70% | 2.94% |
| | | Off-Ramps | 72.2 | 482 | 46.8 | 69.4 | 496 | 49.1 | 2.90% | 4.80% |
| | 25% | Mainstream | 150.5 | 1257 | 56.5 | 146.4 | 1223 | 58.0 | -2.70% | 2.64% |
| | | On-Ramps | 84.3 | 897 | 50.8 | 77.3 | 898 | 55.4 | 0.11% | 9.05% |
| | | Off-Ramps | 73.8 | 609 | 46.0 | 68.6 | 616 | 49.3 | 1.15% | 7.33% |
| 110% | 10% | Mainstream | 146.3 | 477 | 58.1 | 146.5 | 544 | 57.9 | 14.05% | -0.29% |
| | | On-Ramps | 80.8 | 397 | 53.3 | 77.9 | 397 | 55.3 | 0.00% | 3.83% |
| | | Off-Ramps | 73.0 | 231 | 45.7 | 71.2 | 265 | 47.8 | 14.72% | 4.53% |
| | 15% | Mainstream | 147.4 | 705 | 57.7 | 145.9 | 798 | 58.2 | 13.19% | 0.87% |
| | | On-Ramps | 80.0 | 598 | 53.6 | 78.7 | 595 | 54.4 | -0.50% | 1.41% |
| | | Off-Ramps | 70.7 | 362 | 47.3 | 72.7 | 401 | 47.1 | 10.77% | -0.43% |
| | 20% | Mainstream | 148.5 | 954 | 57.2 | 147.7 | 1085 | 57.5 | 13.73% | 0.38% |
| | | On-Ramps | 80.9 | 797 | 52.9 | 77.7 | 798 | 55.0 | 0.13% | 3.96% |
| | | Off-Ramps | 72.0 | 495 | 46.1 | 70.6 | 543 | 48.2 | 9.70% | 4.56% |
| | 25% | Mainstream | 148.4 | 1260 | 57.3 | 148.3 | 1379 | 57.2 | 9.44% | -0.09% |
| | | On-Ramps | 80.5 | 997 | 53.1 | 77.6 | 1000 | 55.1 | 0.30% | 3.79% |
| | | Off-Ramps | 72.4 | 618 | 46.4 | 69.8 | 682 | 48.7 | 10.36% | 4.93% |

The simulation model used for HOV operation analysis under different test scenarios is general and can be applied to similar studies. Further improvements are desired for strengthening the reliability of the results through testing more scenarios. Additionally, more simulation runs are helpful to enhance the creditability of test results.

## REFERENCES


[1] Bureau of Transportation Statistics. *National Transportation Statistics 2007.* U.S. Department of Transportation. Washington, D.C., 2007.

[2] Shrunk, D. and T. Lomax. *The 2005 Urban Mobility Report.* Texas Transportation Institute. The Texas A&M University System (http://mobility.tamu.edu/, access on Jul. 14, 2008). 2005.

[3] Baker, R; D. Ungemah; G. Goodin; and T. Geiselbrecht. Moving beyond Lexus Lanes: Equity Considerations for Managed Lanes. In *the 87th annual meeting of the Transportation Research Board,* CD-ROM. Transportation Research Board, National Research Council, January 13-17, Washington, D.C., 2008.

[4] Kim, A.M., Y. Gardes, and A.D. May, Application of the Paramics Model. In High Occupancy Vehicle Lane Operations. In the *9th World Congress on Intelligent Transport Systems.* Chicago. 2002.

[5] Dahlgren D., High Occupancy Vehicle Lanes: Not Always More Effective Than General Purpose Lanes. *Transportation Research A*, Vol. 32. No. 2. 1998. pp.99-114.

[6] Kwon, J. and P. Varaiya, Effectiveness of High Occupancy Vehicle Lanes in San Francisco Bay Area, University of California, Berkeley and California State University, East Bay, California. 2005.

[7] Fielding J.G. and D. B. Klein. High Occupancy/Toll Lanes: Phasing in Congestion Pricing a Lane at a Time. *Reason Foundation, Policy Study No. 170,* 1993.

[8] Chu, L, K. S. Nesamani, and H. Benouar. Priority Based High Occupancy Vehicle Lanes Operation, In *the 86th annual meeting of the Transportation Research Board,* CD-ROM. Transportation Research Board, National Research Council, January 21-25, Washington, D.C., 2007.

[9] Myron S., and D. Ungemah, So You Want To Make a Hot Lane? The Project Manager's Guide For an Hov-To-Hot Lane Conversion. In *the 85th annual meeting of the Transportation Research Board,* CD-ROM. Transportation Research Board, National Research Council, January 22-26, Washington, D.C., 2006.

[10] Appiah J., and M. W. Burris, QuickRide User Response to Different HOT Lane Operating Scenarios. In *the 84th annual meeting of the Transportation Research Board,* CD-ROM. Transportation Research Board, National Research Council, January 9-13, Washington, D.C., 2005.

[11] Halvorson, R., M. Nookala, and K. R. Buckeye, High occupancy toll lane innovations: I-394 MnPASS. In *the 85th annual meeting of the Transportation Research Board,* CD-ROM. Transportation Research Board, National Research Council, January 22-26, Washington, D.C., 2006.

[12] Mowday, M. Equity and High Occupancy Toll Lanes: A Literature Review and Minnesotans Perceptions About the I-394 High Occupancy Toll Lanes. In *the 85th annual meeting of the Transportation Research Board,* CD-ROM. Transportation Research Board, National Research Council, January 22-26, Washington, D.C., 2006.

[13] Vladisavljevic, I., P.T. Martin, D. Jovanovic, and A. Stevanovic, A High-Occupancy/Toll Lane Experiment on the I-15 in the Salt Lake City Metropolitan Region: A Traffic Flow Evaluation. In *the 87th annual meeting of the Transportation Research Board,* CD-ROM. Transportation Research Board, National Research Council, January 13-17, Washington, D.C., 2008.

[14] Upayokin A., S. Mattingly, and S. Lugo-Serrato. Decision-Making Procedure for Assessing Performance Measures of Freeway Operations. In *the 87th annual meeting of the Transportation Research Board,* CD-ROM. Transportation Research Board, National Research Council, January 13-17, Washington, D.C., 2008.

[15] Appiah, J., B. Naik and M. W. Burris. Multivariate Analysis of High Occupancy/Toll Lane Usage in Houston. In *the 87th annual meeting of the Transportation Research Board,* CD-ROM. Transportation Research Board, National Research Council, January 13-17, Washington, D.C., 2008.

**Table 2 Integrated Simulation Results of HOV Data with the various HOV Proportion under 120% and 130% of the Current Traffic Demands for HOT Lane Segment 4 From 7 Simulation Runs**

| Simulation Time Period: 6:00-9:00 Am | | | HOV Lane Operations | | | HOT Lane Operations | | | Improvement | |
|---|---|---|---|---|---|---|---|---|---|---|
| Traffic Demand | HOV Proportion | Roadway | TT[a] | TP[b] | SP[c] | TT[a] | TP[b] | SP[c] | TP[b] | SP[c] |
| 120% | 10% | Mainstream | 151.6 | 443 | 56.1 | 145.9 | 498 | 58.2 | 12.42% | 3.74% |
| | | On-Ramps | 82.8 | 436 | 51.5 | 79.1 | 435 | 53.8 | -0.23% | 4.37% |
| | | Off-Ramps | 74.7 | 239 | 43.3 | 73.9 | 257 | 44.9 | 7.53% | 3.50% |
| | 15% | Mainstream | 147.1 | 686 | 57.8 | 147.0 | 793 | 57.7 | 15.60% | -0.09% |
| | | On-Ramps | 81.4 | 658 | 52.5 | 78.8 | 659 | 54.2 | 0.15% | 3.34% |
| | | Off-Ramps | 71.1 | 351 | 45.7 | 74.6 | 410 | 45.1 | 16.81% | -1.34% |
| | 20% | Mainstream | 149.8 | 942 | 56.7 | 162.6 | 1097 | 52.2 | 16.45% | -8.02% |
| | | On-Ramps | 85.7 | 877 | 50.1 | 88.6 | 878 | 48.4 | 0.11% | -3.32% |
| | | Off-Ramps | 73.0 | 467 | 46.0 | 74.8 | 553 | 45.5 | 18.42% | -0.92% |
| | 25% | Mainstream | 148.9 | 1239 | 57.1 | 151.9 | 1387 | 55.9 | 11.95% | -2.13% |
| | | On-Ramps | 82.4 | 1098 | 51.9 | 82.0 | 1100 | 52.1 | 0.18% | 0.39% |
| | | Off-Ramps | 70.2 | 632 | 46.9 | 73.2 | 709 | 46.4 | 12.18% | -1.14% |
| 130% | 10% | Mainstream | 149.3 | 483 | 56.9 | 161.6 | 533 | 52.5 | 10.35% | -7.76% |
| | | On-Ramps | 87.7 | 477 | 49.7 | 92.6 | 483 | 48.0 | 1.26% | -3.46% |
| | | Off-Ramps | 87.0 | 251 | 42.8 | 90.0 | 267 | 40.0 | 6.37% | -6.59% |
| | 15% | Mainstream | 150.8 | 694 | 56.4 | 170.1 | 816 | 49.9 | 17.58% | -11.49% |
| | | On-Ramps | 86.1 | 720 | 49.8 | 91.1 | 714 | 46.9 | -0.83% | -5.64% |
| | | Off-Ramps | 73.7 | 360 | 43.9 | 87.7 | 412 | 38.5 | 14.44% | -12.46% |
| | 20% | Mainstream | 154.0 | 949 | 55.2 | 169.4 | 1076 | 50.1 | 13.38% | -9.23% |
| | | On-Ramps | 91.0 | 955 | 46.9 | 120.9 | 951 | 35.4 | -0.42% | -24.46% |
| | | Off-Ramps | 77.6 | 475 | 43.4 | 100.5 | 545 | 33.7 | 14.74% | -22.45% |
| | 25% | Mainstream | 151.2 | 1237 | 56.2 | 205.1 | 1431 | 41.4 | 15.68% | -26.40% |
| | | On-Ramps | 86.3 | 1197 | 49.7 | 168.0 | 1153 | 25.3 | -3.68% | -49.03% |
| | | Off-Ramps | 72.4 | 632 | 46.7 | 116.8 | 722 | 29.4 | 14.24% | -37.14% |


[16] Tilahun, N.Y., and D. M. Levinson. Unexpected delay and cost of lateness on I-394 high occupancy/toll lanes. In *the 87th annual meeting of the Transportation Research Board,* CD-ROM. Transportation Research Board, National Research Council, January 13-17, Washington, D.C., 2008.

[17] Lee D. B. Toward the Evaluation of Value Pricing In *the 87th annual meeting of the Transportation Research Board,* CD-ROM. Transportation Research Board, National Research Council, January 13-17, Washington, D.C., 2008.

[18] Yin, Y., and Y. Lou. Dynamic Tolling Strategies for Managed Lanes. In *the 86th annual meeting of the Transportation Research Board,* CD-ROM. Transportation Research Board, National Research Council, January 21-25, Washington, D.C., 2007.

[19] San Diego Association of Governments. I-15 Express Lanes Traffic – Weekday Daily Average. San Diego, California, April 2005.

[20] Turnbull K. F. High Occupancy Toll (HOT) lanes and Public Transportation. In *the 87th annual meeting of the Transportation Research Board,* CD-ROM. Transportation Research Board, National Research Council, January 13-17, Washington, D.C., 2008.

[21] Zmud J., S. Peterson, F. Douma. Preliminary Before and After Results of the I-394 HOT Lane Panel Survey. In *the 86th annual meeting of the Transportation Research Board,* CD-ROM. Transportation Research Board, National Research Council, January 21-25, Washington, D.C., 2007.

[22] Washington State Department of Transportation, SR 167 - HOT Lanes Pilot Project

[23] Zhang G., S. Yan, and Y. Wang, Simulation-based Investigation on High Occupancy Toll (HOT) Lane Operations for Washington State Route 167. *ASCE Journal of Transportation Engineering*, In Press. August 2009.

[24] PTV. "Vissim User Manual - V.4.30". Karlsruhe, Germany, 2007.

[25] Gabriel G. A. May and R. Horowitz. Congested Freeway Microsimulation Model Using VISSIM. In *Transportation Research Record: Journal of Transportation Research Board, No.1876*, TRB, National Research Council, Washington, D.C., 2004, pp. 71-81.

[26] Zhang, G, Y. Wang, H. Wei and P. Yi, A Feedback-Based Dynamic Tolling Algorithm for High Occupancy Toll (HOT) Lane Operations, In *Transportation Research Record: Journal of Transportation Research Board, No.2065*, TRB, National Research Council, Washington, D.C., 2008, pp. 54-63.

[27] Perrine K., Y. Lao, and Y. Wang "An Area-Wide System for Coordinated Ramp Meter Control" In the 88th annual meeting of the Transportation Research Board, CD-ROM. Transportation Research Board, National Research Council, Washington, D.C., January, 2009.