

A SIMULATION-BASED STUDY ON A LANE-BASED SIGNAL SYSTEM FOR MERGE CONTROL AT FREEWAY WORK ZONES

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ABSTRACT:

This paper presents a new lane-based signal merge (LBSM) control system for freeway work zone operations. The proposed system applies the signal control concept to regulate the vehicles passing the work zone area at a lane-by-lane basis and offers an effective way to maximize the operational efficiency as well as safety. Introduction of the preliminary configuration and principal components associated with the proposed LBSM control contribute the core of this study.

To evaluate the effectiveness of the proposed system, this study has also conducted extensive simulation experiments, based on a freeway simulator calibrated with real-world work zone data. The experimental results show that under heavily congested traffic conditions the LBSM can outperform all existing control strategies with respect to the work zone throughput, the average vehicle delay, the average stop delay, and the average number of stops. This study has also investigated critical traffic flow related factors that may impact on the performance of such a system.

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CE Database subject headings:

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INTRODUCTION

Performing work zone activities in freeway segments is one of the principal contributors to non-recurrent congestion, and it may have a significant impact on traffic mobility as well as safety since the capacity reduction due to lane closures often causes drivers to perform mandatory lane-changing and merging maneuvers. To best manage the traffic approaching and traveling through the work zone, transportation professionals have proposed a variety of merge control strategies over the past two decades including conventional merge (CM), early merge (EM), and late merge (LM). However, how to maximize the operational efficiency and safety of a work zone under high traffic volumes remains a challenging issue.

The CM specified in the Manual of Uniform Traffic Control Devices (MUTCD) (FHWA, 2003) is the most commonly used strategy for work zone operations. The EM (McCoy et al., 1999; Tarko and Venugopal, 2001) seeks to reduce the frequency of forced merge so as to produce smoother traffic flows, while the LM (McCoy et al., 1999; Pesti et al., 1999; Walters et al., 2001; Bearcher et al., 2004; Kang and Chang, 2006) is designed to provide a larger queue storage area and to reduce the frustration levels of drivers. Both EM and LM can be operated in either a static or dynamic form, where the former is to provide an advance notice at a fixed distance ahead of the lane closure, and the latter is to display the message at a location varying with traffic conditions at the work zone (McCoy and Pesti, 2001).

The benefits and limitations of the CM, EM and LM have been extensively discussed in the literatures. In general, the EM seems to perform well in terms of enhancing traffic safety under light and moderate traffic conditions, while the LM can improve the

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operational efficiency mainly under congested traffic conditions (*McCoy and Pesti, 2001; Beacher et al., 2004; Kang et al., 2006*). However, neither EM nor LM can yield the expected effectiveness with respect to traffic safety and mobility under the heavy congestion level. This is due to the fact that the inevitable traffic conflicts resulted from complex merging and lane-changing maneuvers could increase the potential of traffic accidents, and induce stop-and-go movements to degrade the operational efficiency (*Kang et al., 2006*). Moreover, the difficulty for drivers to recognize who has the right-of-way at the merge point may aggravate those traffic conflicts under the heavily congested conditions. Although the advanced speed control such as the variable speed limit (*Lin et al., 2004*) can mitigate those impacts by regulating their average speeds dynamically, it cannot directly control the lane-by-lane merging and lane-changing maneuvers.

This paper explores a new merge control strategy that employs the signal at the proper merging point to assign the right-of-way for traffic in each lane. The problem nature and requirements for applying the proposed lane-based merge control strategy are presented in the next section, followed by a brief description of the proposed system configuration and core control concept in Section 3. Simulation experiments for evaluating the effectiveness of the proposed system along with some tentative research findings are summarized in Sections 4 and 5, respectively.

A LANE-BASED SIGNAL MERGE CONTROL SYSTEM

Right-of-way confusion at the merging point near the work zone taper is widely recognized as one of the main causes to traffic queues and accidents, especially during

congested conditions. The message signs “MERGE HERE” and “TAKE YOUR TURN” are not sufficient for drivers to ensure their right-of-way during the merging processes, especially at the presence of some aggressive drivers. Hence, the merging behavior guided by the variable message signs (VMS) or portable changeable message signs (PCMS) may turn out to be an unsafe and inefficient process, which may in turn result in a substantial capacity reduction. To prevent such undesirable and unsafe merging maneuvers, we propose a new concept of the lane-based signal merge (LBSM) control system in this study.

Concept of the LBSM Control System

The basic concept of the LBSM is to use lane-based signals or variable signs to give drivers in different lanes the right of way to proceed through the open lane(s) in a work zone area. As illustrated in Figure 1, the LBSM that employs either a pre-timed or actuated signal system is to function like an intersection signal control.

The proposed LBSM is expected to achieve the following operational benefits:

- Increase traffic mobility by fully utilizing the open lane capacity;
- Improve traffic safety by using traffic signal to prevent traffic conflicts often incurred to vehicles between the open and closed lanes.

It should be noted that the proposed LBSM system should only be considered in the presence of congestion on the freeway where traffic demand has exceeded the work zone capacity and queues have already formed. Otherwise, the traffic interruptions induced by activating mainline signals on low density-high speed freeways may raise the risk of rear-end collisions and other safety concerns. In addition, additional stops and delays caused by red signals are the price to pay during non-congested traffic conditions.

System Configuration

To produce the aforementioned benefits, the proposed LBSM system should be consistent with the guidelines described in MUTCD. The upstream displayed VMS or PCMS should not be conflicted with the existing static signs, which may otherwise confuse drivers. In this paper, we will discuss only the pre-timed LBSM control system for 2-to-1 highway work zone operations. The configuration and experimental results will serve as the basis for extending its operations to multiple-lane work zones.

System Components

Figure 2 illustrates the principal components of the LBSM control system that consists of:

- A base controller to integrate all system signs/signals and sensors and execute the control commands;
- A set of sensors (SEN-1) for detecting volumes and speeds in each lane, and to activate/deactivate the LBSM system, based on the measured traffic conditions;
- Dynamic Message Signs (DMS-1 and 2) for alerting the approaching drivers (e.g., DMS-1) and directing them to follow the instruction of the lane-use signal;
- A set of Portable Changeable Message Signs (PCMS-1, 2, and 3) to inform the approaching vehicles of the upcoming merging type and the lane-use instructions;
- Overhead Lane-Use Signals (SIGNAL) to assign the right-of-way to the open and closed lanes alternatively;
- Red-light Camera to increase the driver compliance rate;
- Double Solid White Line to prohibit lane-changing maneuvers between the open and closed lanes within the specified distance (e.g., stand-by zone);

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- Transition Zone (TZ) for vehicles on the open and closed lanes to pass and/or merge to the work zone area;
- Stand-by Zone (SZ) for vehicles on the open and closed lanes to wait for their right of ways without changing the lane.

Among the above elements, the lane-use signal, transition and stand-by zones are the most critical components and the subsequent sections will provide the description of their key features.

Lane-Use Signal

Based on the instruction of the lane-use signals, the approaching vehicles shall either proceed through the open lane or stop at the waiting area. To operate such a system effectively, it is essential to inform the upstream traffic flows of the upcoming control type at the work zone. For example, the system should not display any messages of lane closure, but inform drivers of the signal merge control ahead (such as “FOLLOW THE LANE USE SIGNAL AHEAD”, “PREPARE TO STOP BEFORE SIGNALS AHEAD”, and “STAY ON YOUR LANE” / “DO NOT CHANGE LANES”).

For 2-to-1 work zones, a three-phase display (green, amber and red) is sufficient to guide the merging priority of drivers (Figure 2). However, for multiple-lane work zones, it may be necessary to design some type of variable lane-use signs (Figure 3) so that drivers on different lanes can clearly know who have the right-of-way to proceed through the work zone.

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Transition and Stand-by zones

The transition zone is the distance between the first merge taper and the lane-use signals. Its main purpose is to provide enough space for vehicles merging from the closed

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lanes to the open lanes (Figure 4). Note that an excessively long **TZ** may incur the second lane-changing and merging maneuvers. The **TZ** length can be determined from the average speed of approaching vehicles and the work zone geographical characteristics.

It is set as 100 ft in the experimental study.

The stand-by zone is the no-lane-changing area specified with the **white** lines (Figure 5). Note that a SZ of insufficient length may cause multiple merge points and thus diminish the benefits of the LBSM. On the contrary, if the SZ length is excessively long, it may prevent vehicles from balancing the queue lengths between lanes. The most effective distance for a SZ can be determined from the maximum queue length analysis. In this study, we set 500 ft as the baseline.

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PERFORMANCE EVALUATION BASED ON SIMULATION

To ensure that the proposed LBSM can function effectively, this study has developed a simulated system based on the field data which has been well documented at an actual work zone system by the research team with respect to all observed traffic measurements in the previous study (*Kang et al., 2006*). The well-calibrated simulation system serves as the test bed for us to investigate the sensitivity of the LBSM's performance with respect to associated critical factors.

VISSIM 3.7, one of the most sophisticated micro-simulation software developed by Planung Transport Verkehr (PTV), is used as a tool to model the freeway work zone control operations.

Description of the Tested Network

This simulation experiment is based on a freeway segment in Maryland on the U.S. Route I-83 south bound with a right-lane closure work zone near the overpass bridge of Cold Bottom road. It was modeled with VISSIM as a unidirectional two-lane freeway segment consisting of three links, each representing the upstream, work zone, and downstream link. The number of lanes in the work zone link is dropped to one for replicating the one-lane closure area. The model calibration with respect to the upstream volumes, truck percentage, work zone throughput, and average speed at merge point was based on the data collected in 2003 by the research team.

Experimental Design

To evaluate the potential benefits of the LBSM and to investigate its best-applicable traffic conditions, this simulation-based experiment is focused on comparing the performances of CM, static EM, static LM and LBSM in the volume range from 500 vehicles per hour per lane (vphpl) to 1500 vphpl, at an increment of 50 vphpl. In all these tested scenarios, the percentage of heavy vehicles is set as 10%, and the LBSM signals are set to operate with a cycle length of 60 seconds including a red/amber phase of 1 second, an amber phase of 3 seconds and a green phase of 27 seconds for each lane. The traffic control plans of the CM, EM and LM are based on those studies identified in the literature reviews (*FHWA, 2003; McCoy et al., 1999; Pesti et al., 1999*).

This study also included sensitivity analyses to test the impacts of the cycle length and the percentage of heavy vehicles on the effectiveness of the LBSM system. Based on the traffic inflow of 1000 vphpl and the heavy vehicle percentage of 10%, the tested cycle length was set to range from 60 sec to 240 sec at an increment of 30 sec. The study then

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proceeded to check if the results may change with the heavy vehicle percentages (e.g. 5%, 10%, 15% and 20%). Table 1 lists the combination of factors that were examined in the experiments.

The performance evaluation for all the scenarios was based on the following four measurements of effectiveness (MOEs): (1) the hourly work zone throughput (vph); (2) the average delay time per vehicle (sec/veh); (3) the average stop delay per vehicle (sec/veh); and (4) the average number of stops per vehicle (#/veh).

Each scenario was simulated for 4800 sec, including an initialization period of 1200 sec. Each MOE is the average of results from 10 independent simulation replications with different random number seeds for reducing the statistical variance existing in any stochastic simulation program such as VISSIM.

Development and Calibration of Simulation Models

For modeling CM, EM and LM controls with VISSIM, we created a connector to link a lane in the double-lane upstream link with the single lane in the work zone link and specified the lane-choice decision for all entry vehicles (Figure 6a). The lane-changing parameter in the link connector is used to define the distance at which vehicles will begin to change lanes in response to a lane-closure warning sign. For the LM, merge-in-turn will be done automatically (*PTV AG Website, 2006*).

For modeling the LBSM control with VISSIM, this study used two connectors to link each lane in the upstream segment with the lane in the work zone area (Figure 6b). A traffic signal was set at each of the two connectors. Since vehicles running in one connector cannot change to another connector, the simulated system can replicate a non-lane-changing stand-by zone from the starting point of the connectors to the location of

signals. As a result, driver compliance rate to the LBSM is close to 100% in the simulation models. Note that the focus of this study at this stage is to evaluate the system effectiveness with the assumption that all drivers are willing to follow the instructions under the surveillance of some monitoring devices.

Simulation parameters to be calibrated for the models are the upstream volumes, heavy vehicle percentage, and two driving behavior parameters in the upstream link, the minimum headway distance for the lane-changing behavior and the headway time that a driver wants to keep at a certain speed for the car-following behavior (Wiedemann 99 car-following model, VISSIM 3.7 User Manual, 2003). We have performed the search for these four parameters over a wide range of possible values until the simulated work zone throughputs and average speeds at merge points are consistent with the field data collected at the I-83 work zone site under the CM and LM controls.

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Table 2 presents the calibration results for the simulated highway work zone, based on the field observed traffic information. The results indicate that the calibrated simulation system can realistically reflect the actual work zone traffic conditions around the merge point under the CM and LM controls.

Table 3 presents two sets of parameters calibrated for driver behaviors, one for those under CM and EM and the other for those under LM and LBSM, as the control strategies in each set share the similar operational characteristics.

Analysis of Simulation Results

Performance Comparison between Different Control Strategies

The comparison between LBSM and three existing merge control strategies (CM, EM and LM) based on the four selected MOEs under varying traffic volumes are shown in Figure 7. It is clear that the work zone capacity under the EM, CM, LM and LBSM

control with the cycle length of 60 sec is about 1400, 1500, 1600 and 1800 vphpl, respectively, given the 10% heavy vehicles in the traffic flows.

As reflected in Figure 7a, the work zones with the LBSM always yield higher throughputs than those under the LM. This is expected since the LM can be viewed as a special case of LBSM with a very short cycle length under the forced flow conditions. The results in Figure 7 are also consistent with our expectation that the LBSM can achieve significant benefits, especially under heavily congested traffic conditions.

To explore the traffic condition best appropriate for each control strategy, this study has further conducted the following four sets of experiments:

- **Light volume level (500~700 vphpl)**

As shown in Figure 8, when the entry traffic volumes are less than the EM capacity ($700 \times 2 = 1400$ vphpl), the CM and EM outperform LM with respect to higher work zone throughputs and they also outperform LBSM with respect to lower delays and less number of stops. No significant difference exists between CM and EM, based on the simulation results. In general, considering the traffic safety benefit, EM seems more desirable than others at this volume level.

Under the same range of light traffic volume, the LM control produces the lowest work zone throughput. This is likely due to the fact that under light traffic condition, most vehicles can easily find acceptable gaps to merge into the open lane without disturbing the traffic flows. Hence, the “merge-in-turn” instruction with the LM control under light volumes may excessively interrupt the traffic flow and decrease the merging efficiency.

The LBSM control exhibits no significant improvement over CM and EM and has only slight improvement over LM with respect to the work zone throughput. Furthermore, the LBSM results in the highest average vehicle delay, stop delay, and number of stops

among the four control systems. This clearly indicates the fact that placing a signal control at the work zone will cause excessive traffic queue and delay if the approaching volume is not sufficiently high to justify doing so.

- **Modest volume level (700~750 vphpl)**

When the entry traffic volume exceeds the EM capacity ($700 \times 2 = 1400$ vph) but less than the CM capacity ($750 \times 2 = 1500$ vph), the CM seems to achieve satisfactory performances on the throughputs, delays and the number of stops (see Figure 9). Under this range of modest volumes, neither the LBSM nor the LM exhibits any substantial benefits over the CM.

As expected, the EM performs worse than the CM with respect to all MOEs, as at this volume level vehicles will begin to experience the difficulty in changing lanes and consequently cause traffic disturbances. Implementation of the EM under such traffic conditions may result in numerous merging points and yield negative impacts on the operation efficiency.

- **High volume level (750~800 vphpl)**

When the total entry traffic volumes exceed the CM capacity and approach the LM capacity, the LM outperforms EM and CM with respect to all four MOEs (see Figure 10).

Note that the work zone throughput under the LBSM in this range of volume is slightly higher than that under the LM. However, the improvement is not sufficiently significant as to compensate for the increase in the average delay, stop delay, and the number of stops.

Based on the resulting throughput and disturbance to the traffic flow, it is reasonable to view the LM as the most suitable control strategy under this range of volumes.

- **Congested volume level (800~1500 vphpl)**

As shown in Figure 11, when the traffic demands exceed the capacity of the LM, the LBSM control substantially outperforms the other three control strategies. On average, its resulting work zone throughput is about 30% higher than that under the EM, 22% more than the CM and 12% over the LM. The reduction in the average delay is 41% compared to the EM, 39% and 29% when compared with the CM and the LM, respectively. The decreases in the average stop delay and the number of stops are also remarkable.

At this volume level, traffic is heavily congested at the upstream point of the blockage link and a long queue may exist in both lanes. Since the LBSM control provides a rule to assign the right-of-way to vehicles in the queues, it can mitigate most merge conflicts and best use the available capacity of the open lane. Such a control strategy may also reduce the stop delay and number of stops as it prevents the likelihood of having multiple merge points.

Sensitivity Analysis with Different Cycle Lengths

In the example of two-lane highway with one lane closure, the LBSM system employs two phases to regulate the movement of vehicles in the two upstream lanes. Figure 12 displays the performance results of the LBSM under different cycle lengths with the upstream demand of 1000 vphpl and the heavy vehicles of 10%.

The numerical results reflect that the cycle length of 120 sec (2 minutes) yields the highest throughput, the lowest average vehicle delay, the least number of stops, and a low average stop delay. In general, a short cycle length may result in less efficient use of the green times, but excessively long cycle length may incur long queues. Usually, an optimal cycle length can be found in the same way under different traffic conditions.

Sensitivity Analysis with respect to the Impacts of heavy vehicles

The performance results of the LBSM control system under various heavy vehicle percentages at the volume level of 1000 vphpl are shown in Figure 13.

The graphical results clearly indicate that the presence of heavy vehicles will significantly degrade the operational efficiency of the work zone on all aspects under the LBSM. The optimal cycle length for such a control system seems to increase with the percentage of heavy vehicles. For example, the best cycle length increases from 90 sec to 150 sec when the truck percentage increases from 5% to 20%. This is likely due to the fact that the average headway in the traffic flow often increases due to the presence of heavy vehicles, and thus a longer cycle length is needed to increase the throughput and improve other MOEs.

CONCLUSIONS AND FUTURE STUDIES

This study has employed a well-calibrated simulation system to explore the best control strategy designed for work zone operations under different volume levels. Through extensive experiments, this study has confirmed the general belief that the work zone control shall evolve along the sequence of early merge, conventional merge, to the late merge control when the incoming traffic volume increases over time. For example, for the test network, the early merge control is preferable under the range of volumes below 700 vphpl; the conventional merge control can perform satisfactorily when the volume ranges from 700 to 750 vphpl; the late merge control can best achieve its effectiveness under the volume range between 750 and 800 vphpl.

Our research has also indicated that the above three merge controls can no longer be effective if the approaching volume exceeds 800 vphpl. Hence, this study has proposed

an innovative design that employs a signal-based control to regulate the movement of vehicles waiting to proceed through the work zone under congested volume levels.

Our extensive simulation evaluation with respect to the proposed LBSM has clearly indicated that the design, even preliminary in nature, can significantly increase the throughput and result in a reduction in the average vehicle delay, average vehicle stop delay and the number of vehicle stops under congested traffic conditions. Because of its potentially higher capacity which reduces the queue presence and the time when the backward shockwave is present on the approach to the freeway, the proposed system may also mitigate crash risk at the end of the queue (backward shockwave).

The experimental results have also revealed that the optimal cycle length for the LBSM control seems to increase with the percentage of heavy vehicles in the traffic flows.

Despite the promising properties of the proposed LBSM control, the authors fully recognized that much remains to be done to promote the implementation of such a new design. For instance, well-designed field demonstrations will be needed to explore the impact of several critical factors on the system efficiency, including the optimal length for the transition zone and stand-by zone, the control limit of the upstream speed, and the enforcement design to increase the driver compliance rate. One shall also explore the potential of developing an advanced actuated LBSM system for regulating the merging operations at the work zone of multiple lanes and a dynamic merge control system which can automatically switch among EM, CM, LM and LBSM according to real-time traffic conditions.

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REFERENCES

- 1 Beacher, A. G., Fontaine, M. D., and Garber, N. J. (2004). "Evaluation of the Late Merge Work Zone Traffic Control Strategy." *Research Project No. VTRC 05-R6*, Virginia Transportation Research Council, sponsored by the U.S. Department of Transportation.
- 2 Federal Highway Administration. (2003). *Manual on Uniform Traffic Control Devices*, U. S. Department of Transportation, Washington, D. C.
- 3 Kang, K. P. and Chang, G. L. (2006). "Development of an Advanced Dynamic Late Merge Control Model and Algorithm." *Transportation Research Board Annual Meeting (CD-ROM)*, Washington, D.C.
- 4 Kang, K. P., Chang, G. L., and Paracha, J. (2006). Dynamic Late Merge Control at Highway Work Zones: Evaluations, Observations, and Suggestions. *Transportation Research Record, No. 1948*, TRB, National Research Council, Washington, D.C., 86-95
- 5 Lin, P.W., Kang, K.P., and Chang, G.L. (2004). "Exploring the Effectiveness of Variable Speed Limit Controls on Highway Work-Zone Operations." *Intelligent Transportation Systems*, 8, 1-14.
- 6 McCoy, P. T., Pesti, G., and Byrd, P. S. (1999). "Alternative Driver Information to Alleviate Work Zone-Related Delays: Final Report." *NDOR Research Project No. SPR-PL-1(35) P513*, Department of Civil Engineering College of Engineering and Technology, sponsored by Nebraska Department of Roads.

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- 7 McCoy, P.T. and Pesti, G. (2001) “Dynamic Late Merge Concept for Work Zones on Rural Interstate Highways.” *Transportation Research Record, No. 1745*, TRB, National Research Council, Washington, D.C., 20-26.
- 8 Pesti, G., Jessen, D. R., Byrd, P. S. and McCoy, P. T. (1999). “Traffic Flow Characteristics of the Late Merge Work Zone Control Strategy.” *Transportation Research record, No. 1657*, TRB, National Research Council, Washington, D.C., 1-9.
- 9 PTV AG. (2006) “VISSIM FAQ.” <http://www.english.ptv.de/cgi-bin/traffic/traf_vissimfaq.pl#1%20Installation> (Oct.9, 2006)
- 10 Tarko, A. and Venugopal, S. (2001). “Safety and Capacity Evaluation of the Indiana Lane Merge System.” *Research Project No. FHWA/IN/JTRP-2000/19*, Joint Transportation Research Program, Purdue University, sponsored by Indiana Department of Transportation.
- 11 VISSIM 3.70 User Manual. (2003). PTV Planung Transport Verkehr AG, Karlsruhe, Germany.
- 12 Walters, C. H., and Cooner, S. A. (2001). “Understanding Road Rage: Evaluation of Promising Mitigation Measures. Report 4945-2. Texas Transportation Institute, College Station.

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Table 1: Variables Tested in the Simulation Experiment

Test Factor	Number of Level	Value of the Test Factors			
		Min	Max	Increment	Baseline
Approaching Volume (vphpl)	21	500	1500	50	1000
Cycle Length (sec)	4	60	240	30	60
Truck Percentage (%)	4	5%	20%	5%	10%

Table 2: Comparison of Field Data with Simulation Results

Calibration Scenarios Traffic conditions	CM (10/10/2003)		LM (10/22/2003)	
	Field Data	Simulation Results	Field Data	Simulation Results
Upstream Volume (vph)	1875	1875	1887	1887
Heavy Truck Percentage (%)	19%	19%	17%	17%
Work Zone Throughput (vph)	1340	1346	1469	1478
Average Speed at Merge Point (mph)	24	25	17	16.9

Table 3: Driver Behavior Parameters Calibrated in the Simulation Models

Calibrated Parameters in the work zone upstream link	CM and EM	LM and LBSM
Min Headway (ft)	17.21	11
Headway Time (s)	1.7	1.2

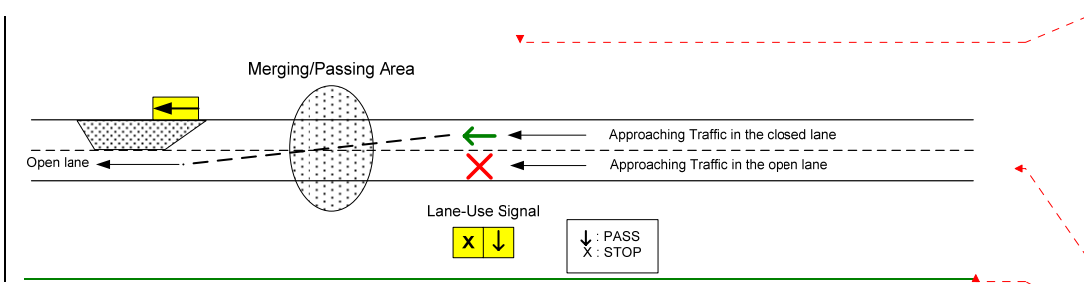


Figure 1: Concept of the LBSM at Freeway Work Zones

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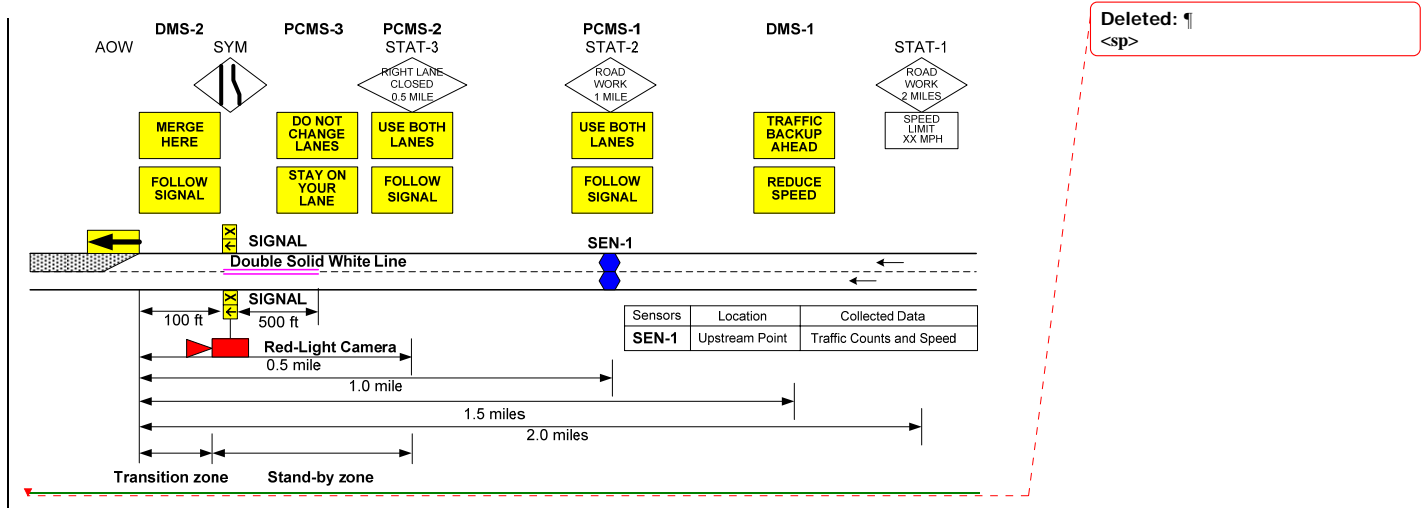


Figure 2: System Configuration of the LBSM Control System

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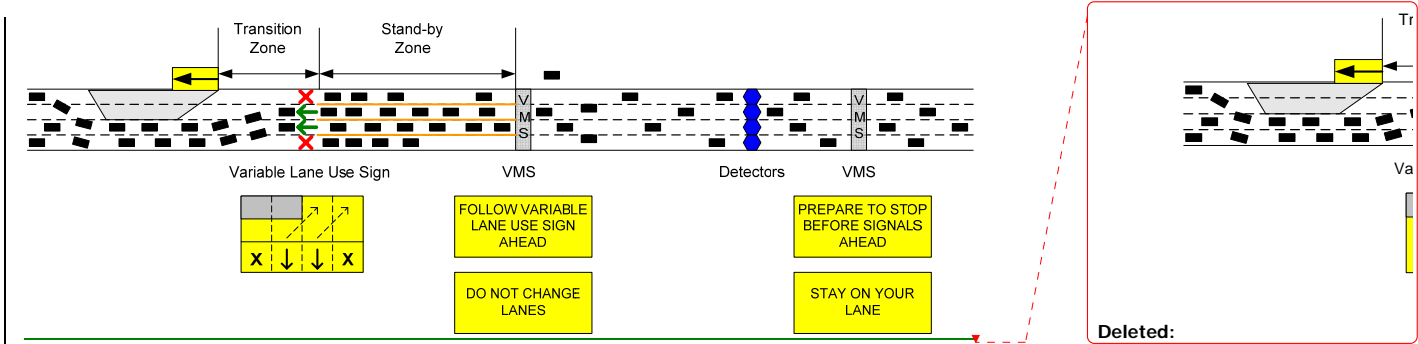


Figure 3: Preliminary Configuration of the LBSM in Multiple-Lane Highways

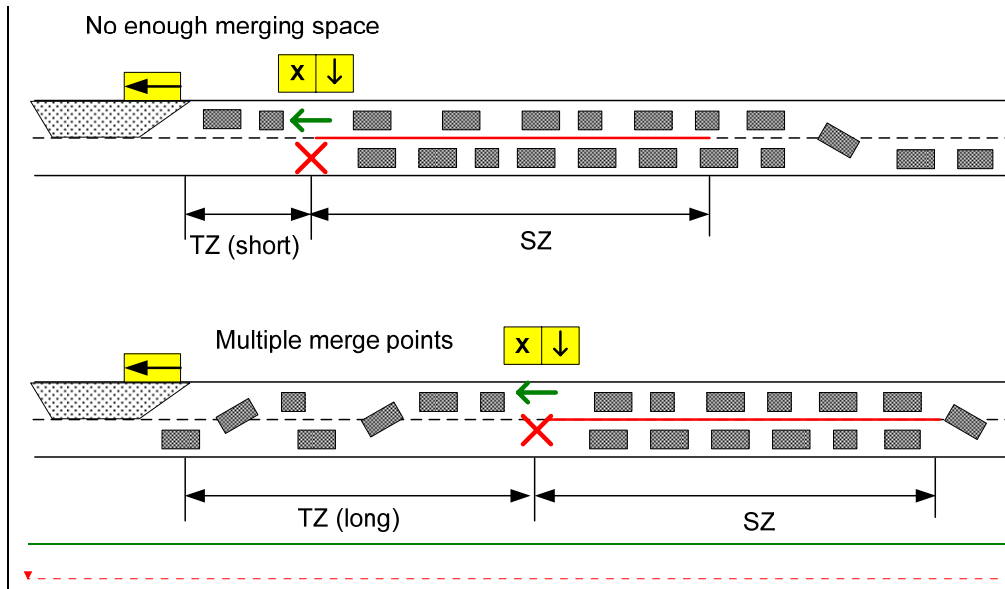
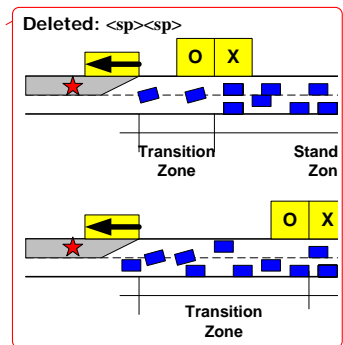


Figure 4: Transition Zone (TZ) between the Merge Taper and the Lane Use Signal



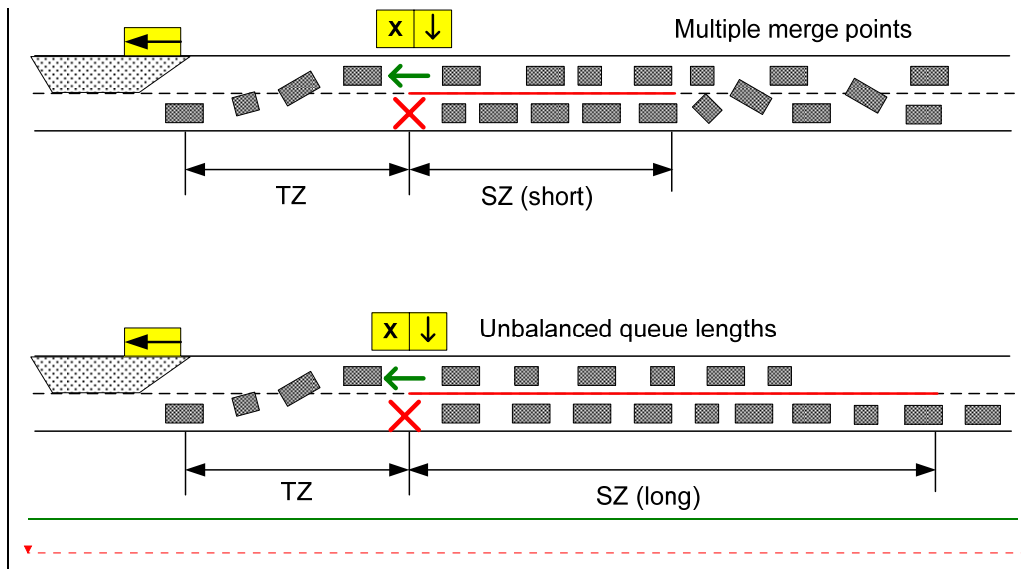
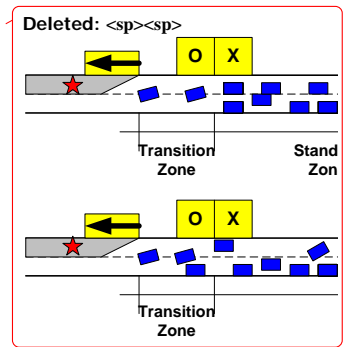


Figure 5: Stand-by Zone (SZ) in the Upstream Segment of the Work Zone



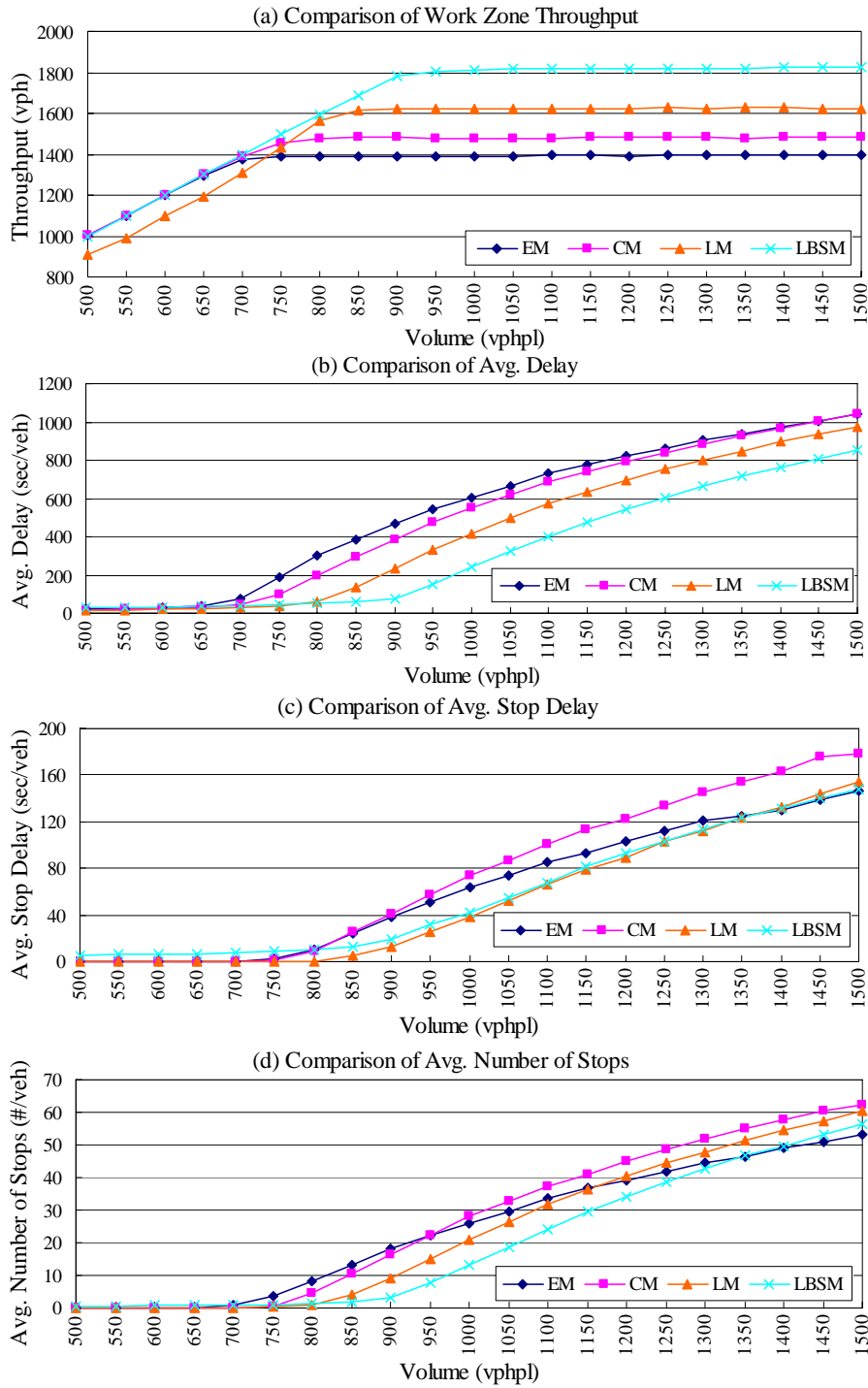


Figure 7: Performance Comparison of CM, EM, LM and LBSM (500-1500 vphpl)

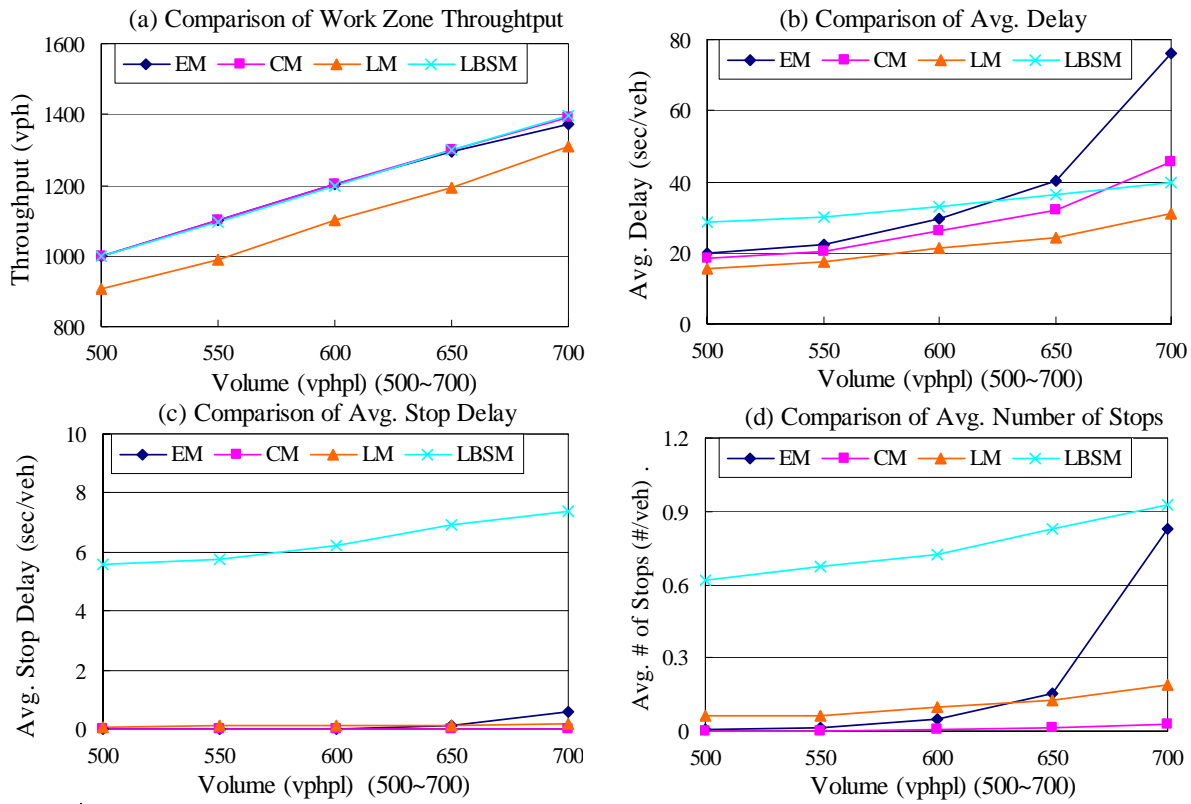


Figure 8: The Performance Comparison at Light Volume Level (500~700 vphpl)

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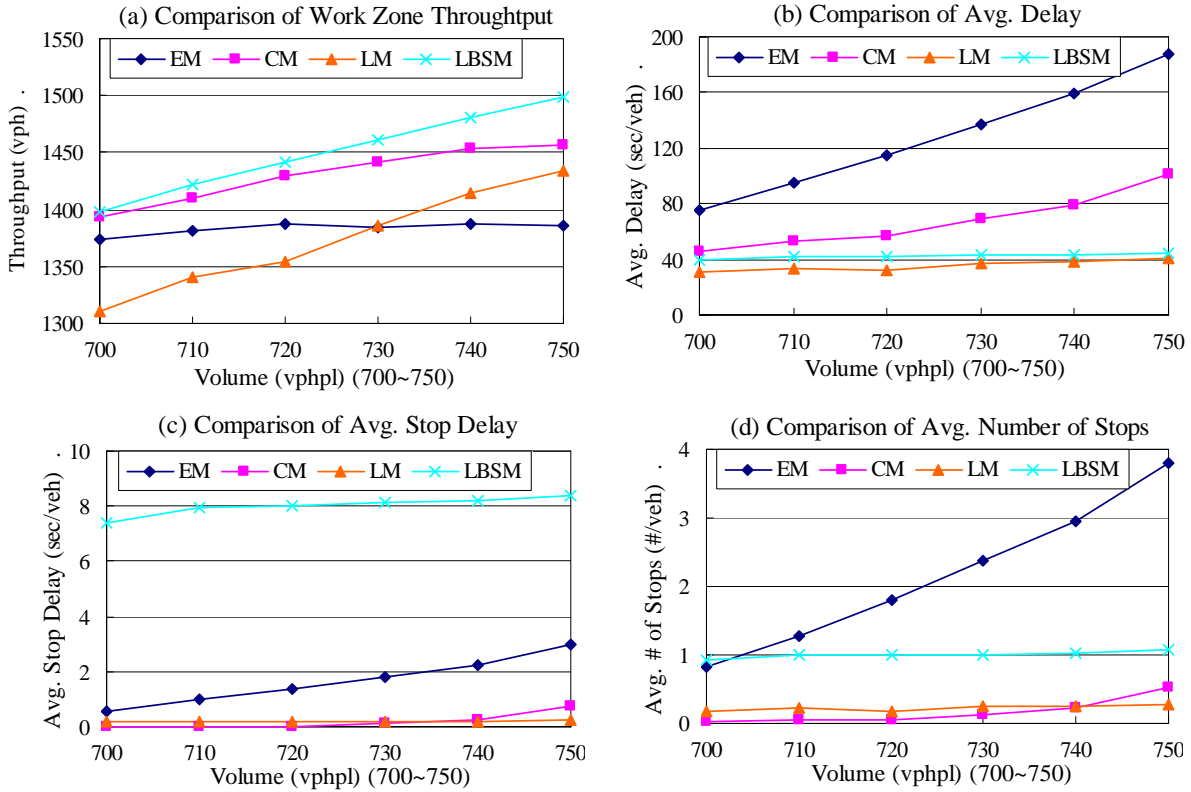


Figure 9: Performance Comparison at Modest Volume Level (700~750 vphpl)

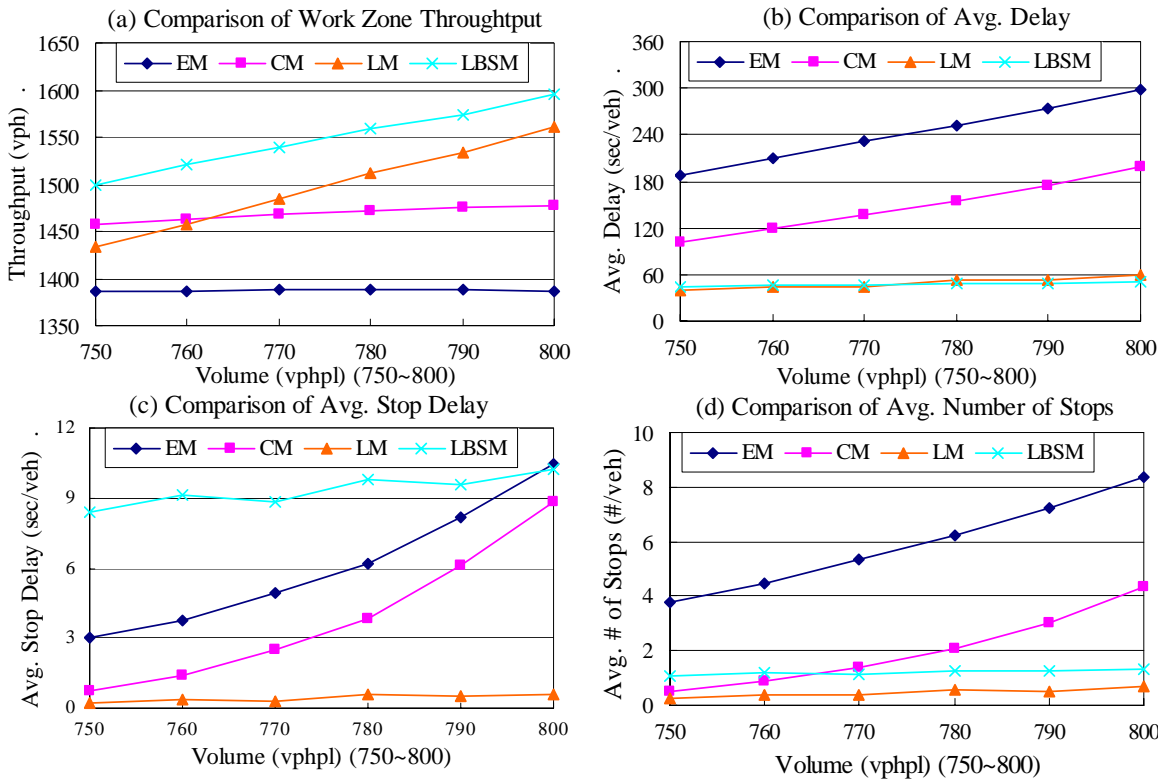


Figure 10: Performance Comparison at High Volume Level (750~800 vphpl)

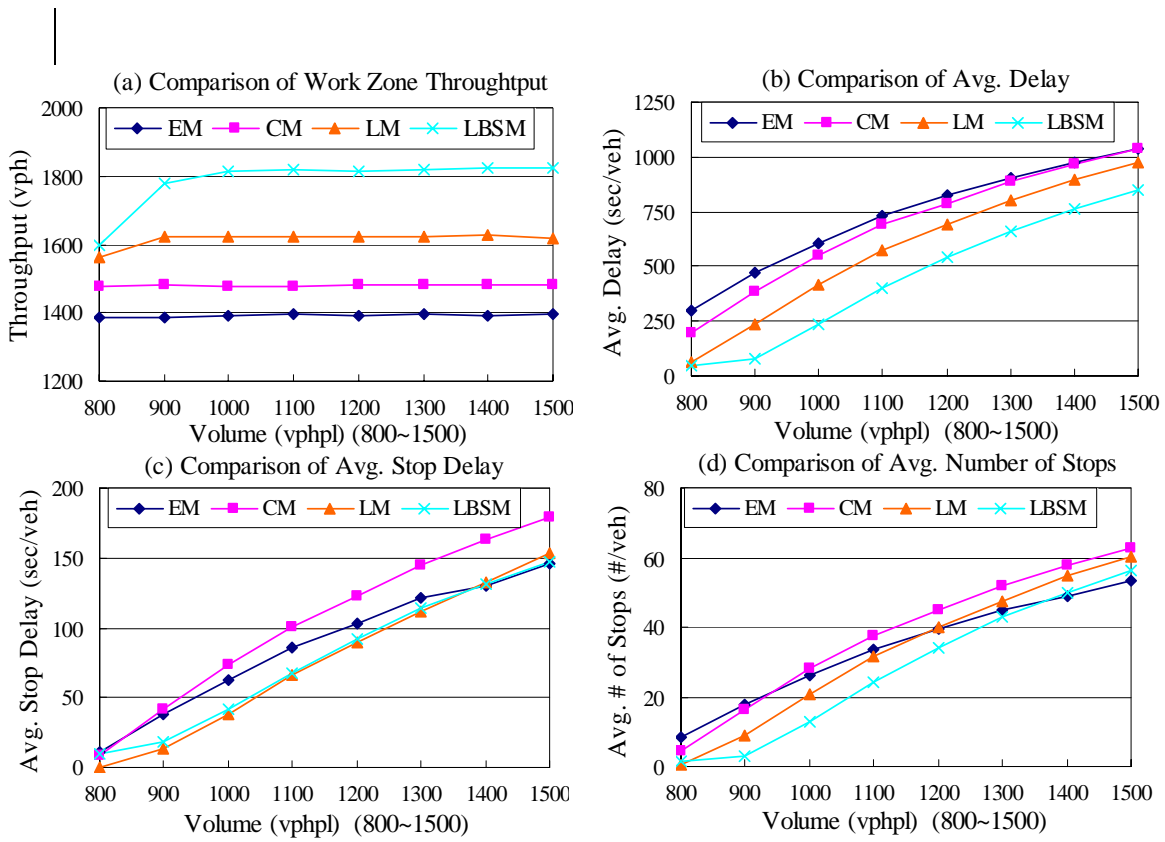


Figure 11: Performance Comparison at Congested Volume Level (800~1500 vphpl)

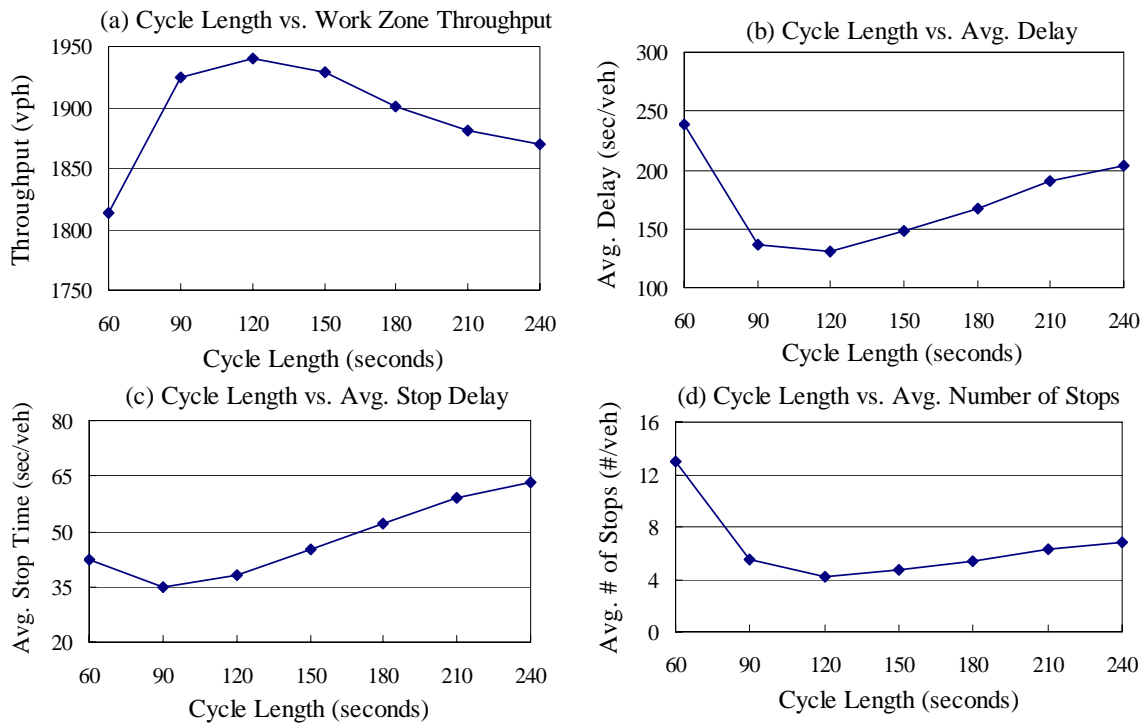


Figure 12: Performance of the LBSM with Various Cycle Lengths

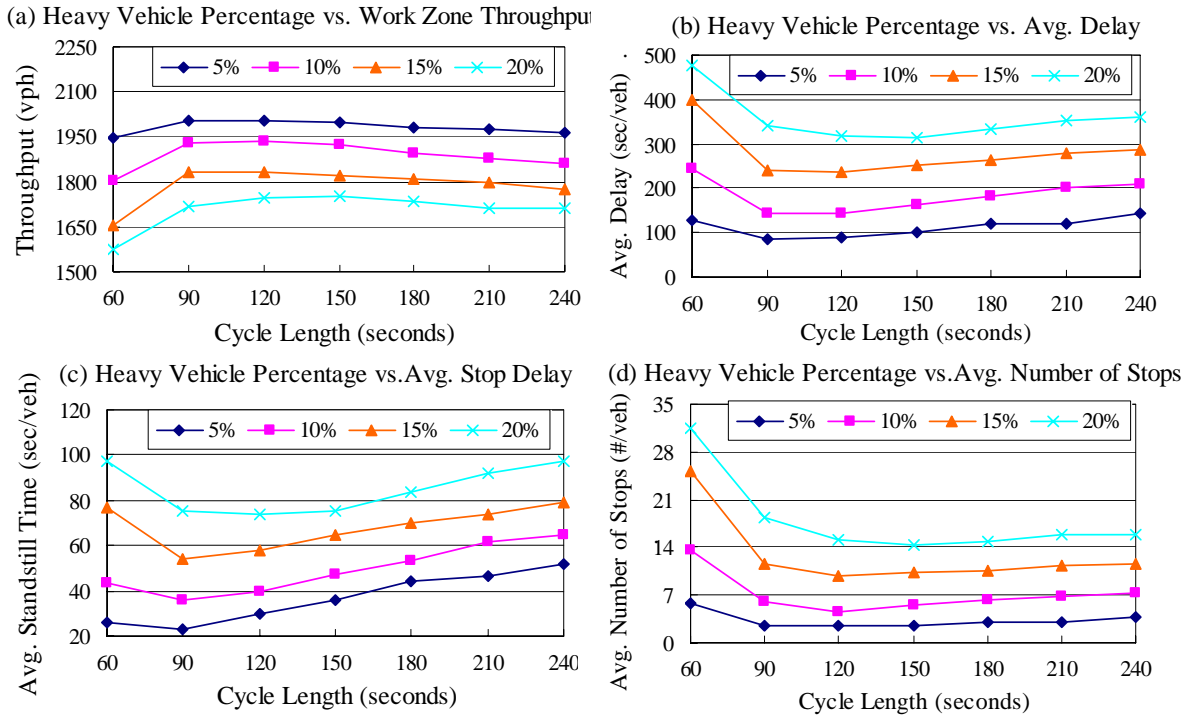


Figure 13: Performance of the LBSM with Various Heavy Vehicle Percentages