PART I
EVALUATION OF A DYNAMIC LATE MEREGE SYSTEM

1. Overview of Dynamic Late Merge Systems

1.1 Core concept of Dynamic Late Merge control

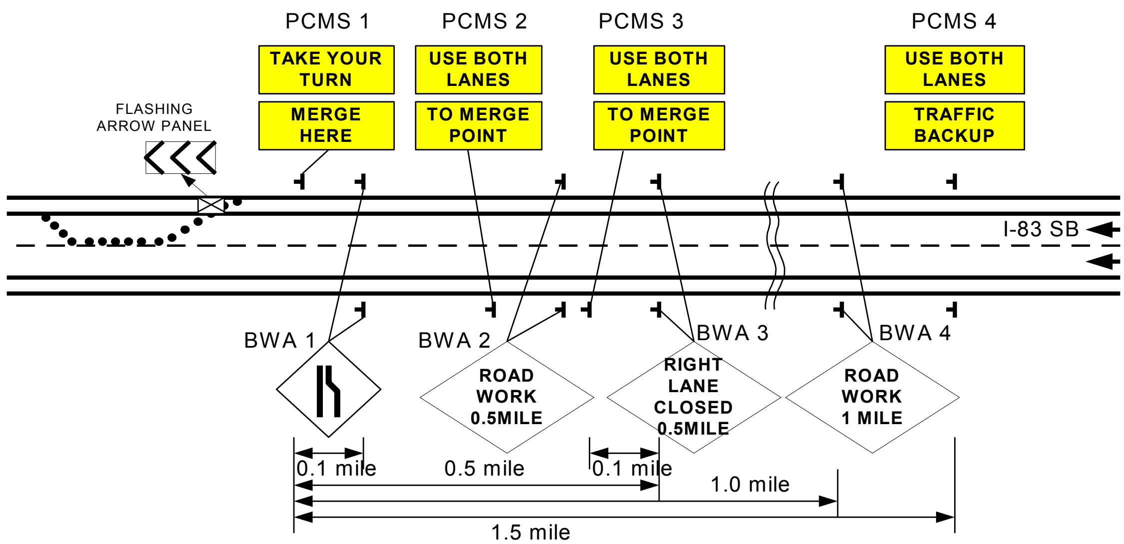

Figure 1-1: Configuration of the DLM system

A Dynamic Late Merge system generally consists of a series of variable message signs that will be activated or deactivated based on real-time measurements of traffic conditions.

Dynamic Late Merge (referred to as DLM), as shown in Figure 1-1, is designed to provide safe merging operations under congested traffic conditions. It has the following key system features:

- Using PCMS (Portable Changeable Message Signs) to display messages to motorists when the DLM system is active (i.e., "USE BOTH LANES" and "TO MERGE POINT");
- Employing traffic sensors such as RTMS (Remote Traffic Microwave Sensor), placed at the same locations as PCMS 1, 2 and 3 for detecting traffic conditions in real time;
- It is generally operated alone with static warning signs (i.e., BWA 1, 2, 3 and 4), which are similar to those used in conventional work zone control (referred to as No-control) proposed by NDOR (Nebraska Department of Roads) for informing approaching motorists of the lane closure when the DLM system is not active.

1.2 Deployment of the tested DLM system

The proposed DLM system was deployed prior to a right-lane closure in a work zone area near the overpass bridge of Cold Bottom Road on I-83 SB (see Figure 1-2).

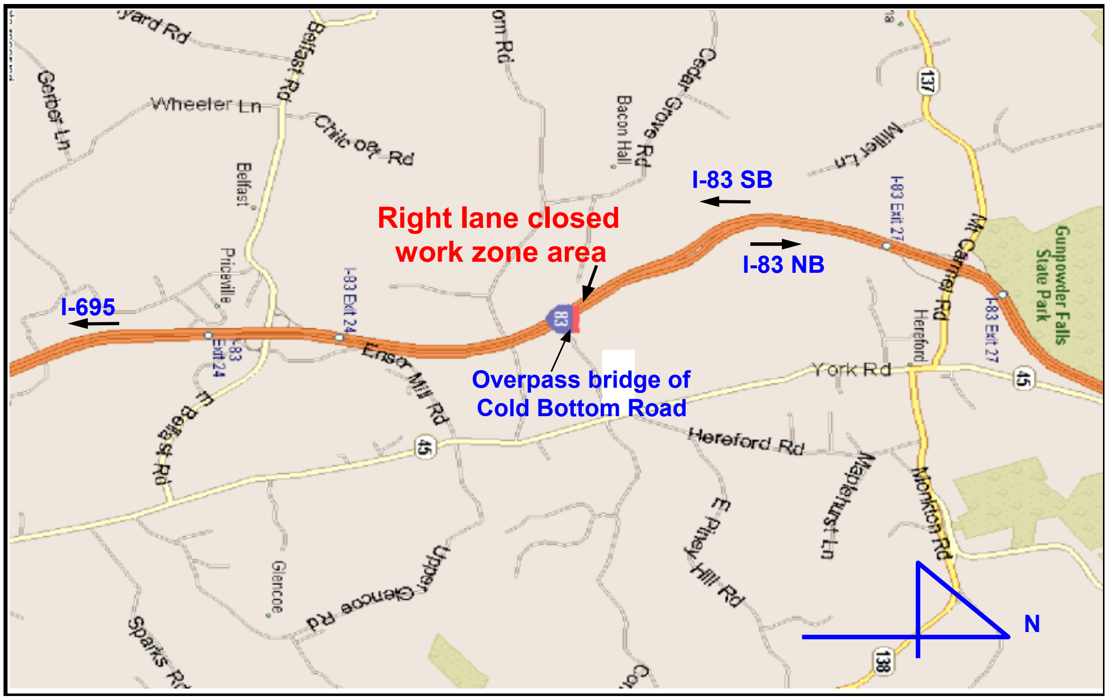

Figure 1-2: Location of the work zone on I-83 SB, near Cold Bottom Road

1.3 Algorithms and control thresholds

The DLM system tested by MSHA (Maryland State Highway Administration) and IRD (International Road Dynamics) had the capability to operate with four algorithms (see Table 1-1), based on the occupancy detected by each RTMS in the DLM Control System.

During the test, the proposed DLM system in the actual field test was operated by the “All On – All Off” algorithm, that is, all PCMS were deactivated (i.e., No-control) if all occupancies were below 5% (e.g., Figure 1-3), and all PCMS would be activated (i.e., DLM control) as long as the occupancy among any of the deployed sensors was over 15% (e.g., Figure 1-4).

Table 1-1: Four Algorithms for DLM control

Algorithms	Occupancy	
	Deactivated	Activated
1. Dynamic On – Dynamic Off (Early lane merge)	5% (Free flow index)	15% (Congestion index)
2. Dynamic On – Dynamic Off		
3. All On – All Off		
4. Dynamic On – All Off		

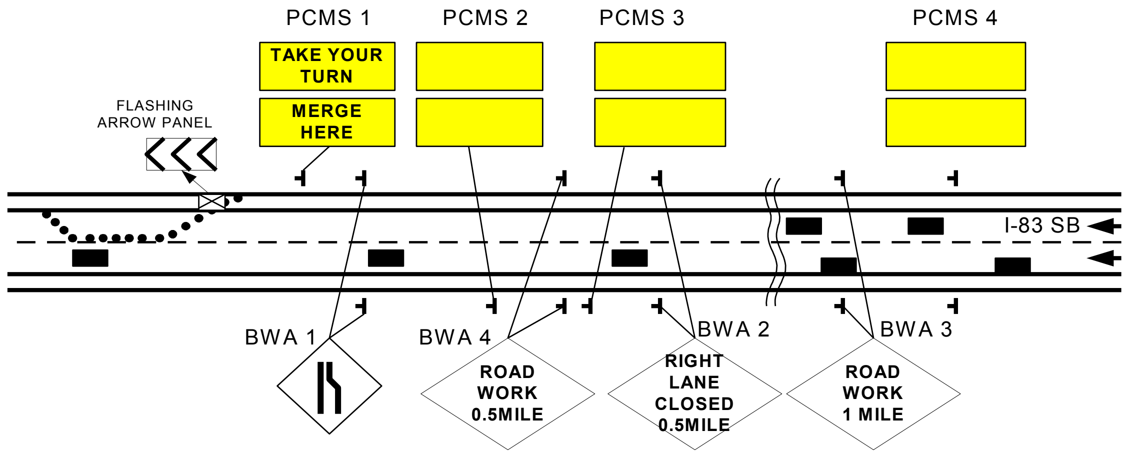

Figure 1-3: System deactivation under free flow traffic conditions

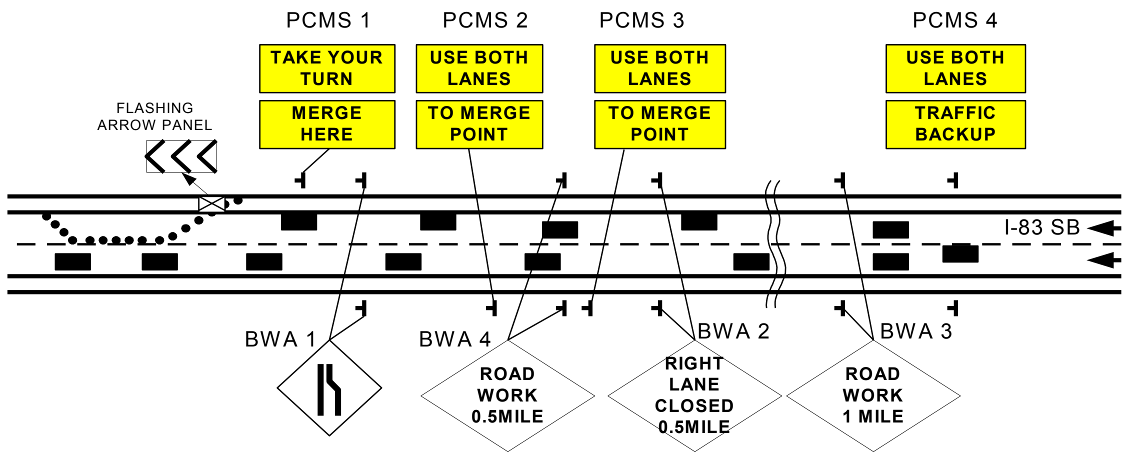

Figure 1-4: System activation under congested flow traffic conditions

2. Data Available for Evaluation

Due in part to bad weather conditions and operational problems, system performance data with acceptable quality was only available for one day under No-control (i.e., before the DLM control) and for four days under the DLM control.

Field data for evaluation was gathered with three camcorders (see Figure 2-1 for camcorder locations) and focused on capturing volume data, merge behavior, traffic conflicts, and queue lengths. In addition, two speed guns were used to measure the distribution of spot speeds. The camcorders were installed at the merge point (i.e., Camcorder 1 and PCMS 1) close to the beginning of the taper, at the middle point (i.e., Camcorder 2 and PCMS 3) about 0.5 mile before the taper, and at the upstream point (i.e., Camcorder 3 and PCMS 4) about 1.5 miles away from the lane closure location (also see Figure 1-1). Speed samples were collected at the merge and middle points. The data collection plan is summarized in Table 2-1. Traffic flow data such as volume, speed, and occupancy were also available from RTMS for system performance evaluation under the DLM control.

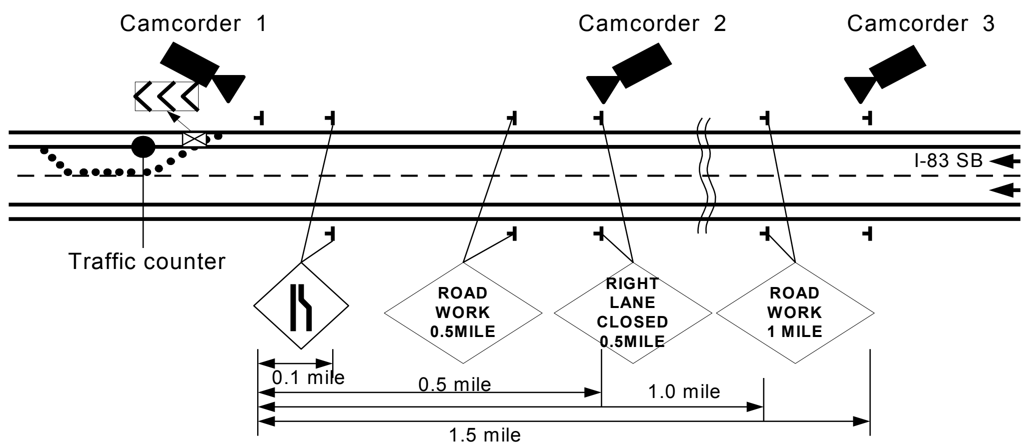

Figure 2-1: Locations of the camcorders

Table 2-1: Data available for the DLM system evaluation

Measures of Effectiveness	Data types	Locations	Methods
Work zone throughput	Volume	Merge point	Traffic counter and RTMS
Lane volume distribution	Traffic counts	Merge, middle, and upstream points	Camcorders 1 and 2, and RTMS
Queue length	Maximum queue length	Merge, middle, and upstream points	Camcorder 3
Speed distribution	Speed	Merge and middle points	Speed gun and RTMS
Traffic conflicts	Forced merge Lane straddle Lane blocking Stop and go	Merge and middle points	Camcorders 1 and 2

3. Evaluation of Sensor Accuracy

3.1 Volume data

Figures 3-1 to 3-4 compare the sensor detected data and manually counted volumes for the open and closed lanes at the merge and middle points, respectively. The results clearly indicate that the volumes detected by sensors for both the open and closed lanes differ significantly from those counted directly from video tapes.

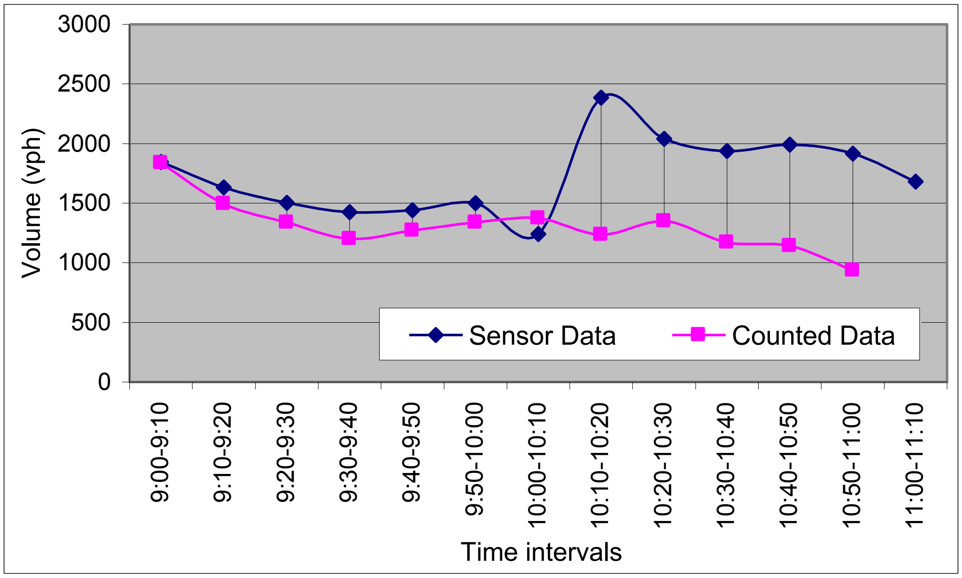

Figure 3-1: Comparison of volume data on the open lane (Merge point, 10/22/2003)

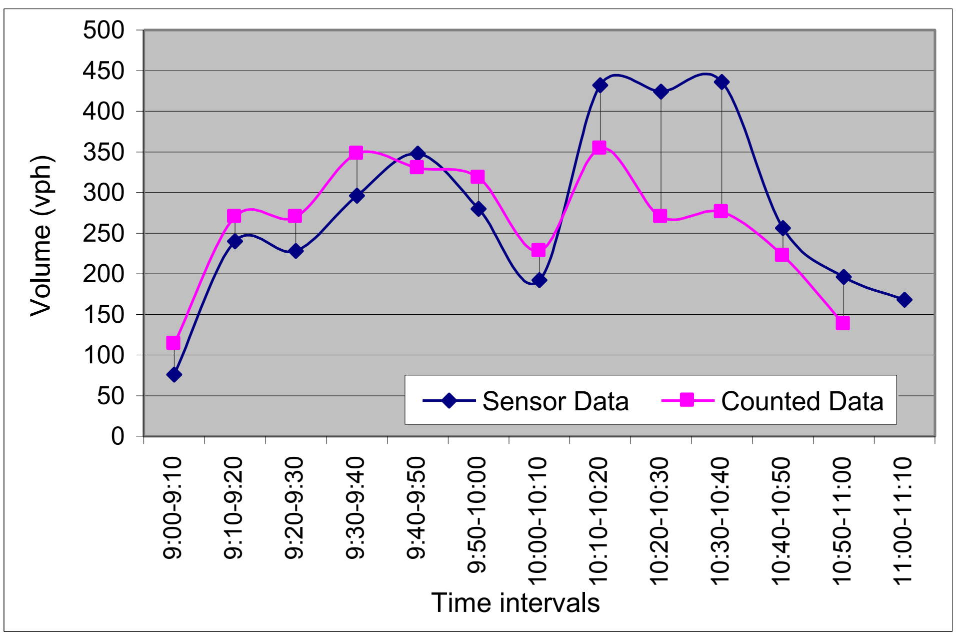

Figure 3-2: Comparison of volume data on the closed lane (Merge point, 10/22/2003)

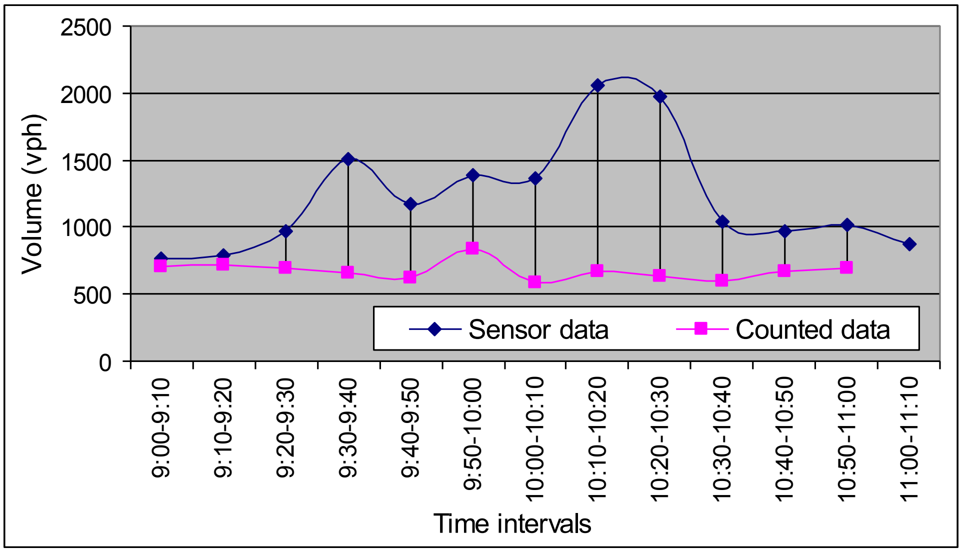

Figure 3-3: Comparison of volume data on the closed lane (Middle point, 10/22/2003)

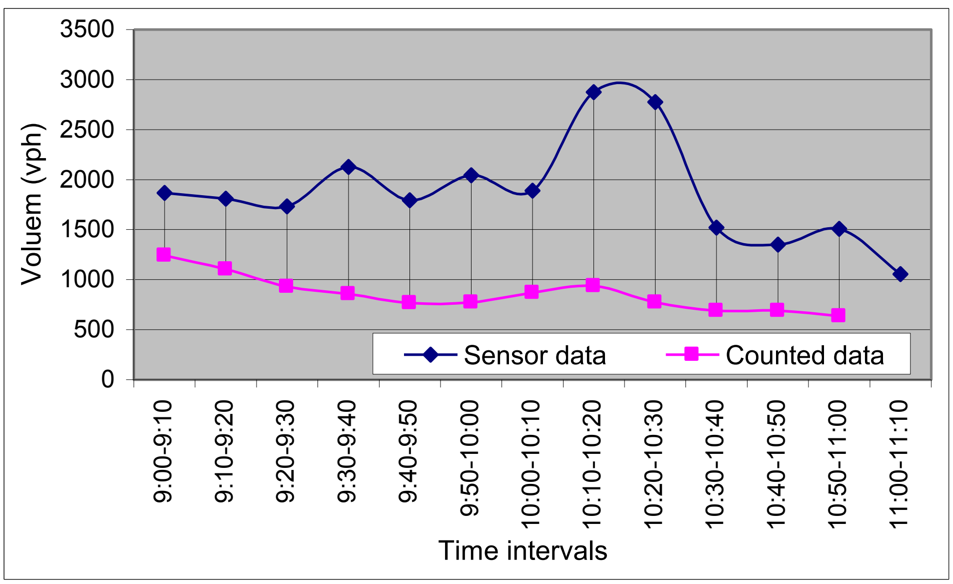

Figure 3-4: Comparison of volume data on the open lane (Middle point, 10/22/2003)

Overall, it appears that those RTMS were not calibrated properly. This is evident in the results summarized in Table 3-1.

Based on these comparison results, one may conclude that the volume data detected by the RTMS are not reliable, and should not be used in the performance analysis. Instead, it is more reliable to measure volume related information directly from video tapes.

Table 3-1: Summary of volume differences between sensors and manually counted data

10/22/2003				
Locations		**Manual**	**Sensor**	**Difference**
Merge point	Open lane	1307	1738	33%
	Closed lane	262	284	8%
Middle point	Open lane	856	1941	127%
	Closed lane	673	1251	86%
10/23/2003				
Locations		**Counted**	**Sensor**	**Difference**
Merge point	Open lane	1330	1454	9%
	Closed lane	348	338	-3%
Middle point	Open lane	811	1706	110%
	Closed lane	726	1305	80%

3.2 Speed data

Figures 3-5 to 3-12, respectively, present the distributions of speed on the open and closed lanes under No-control and DLM control. It should be noted that the speed distributions on 10/10/2004 were measured with speed guns, and the distribution on all other dates were based on data measured by RTMS.

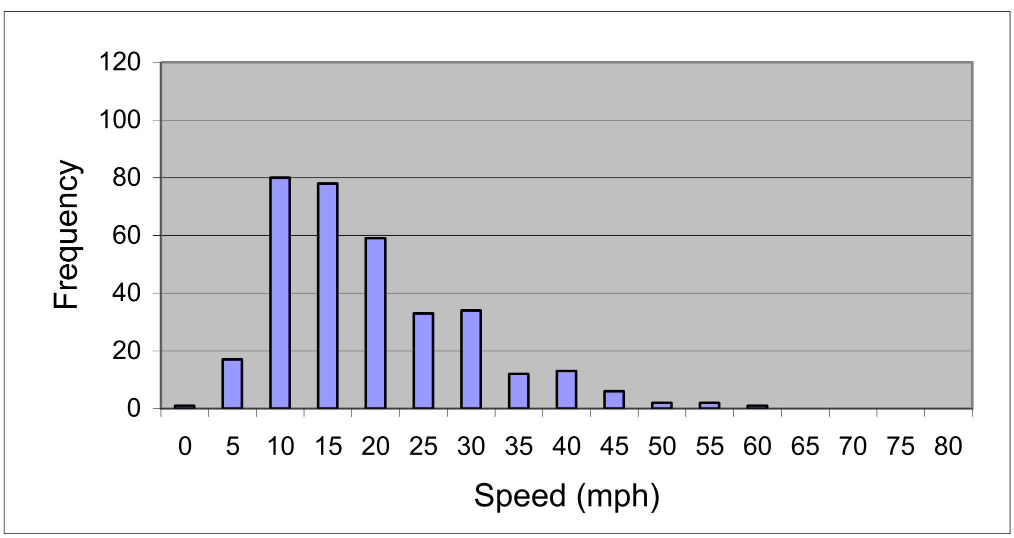

Figure 3-5: Speed distribution on the closed lane (Merge point, 10/10/2003)

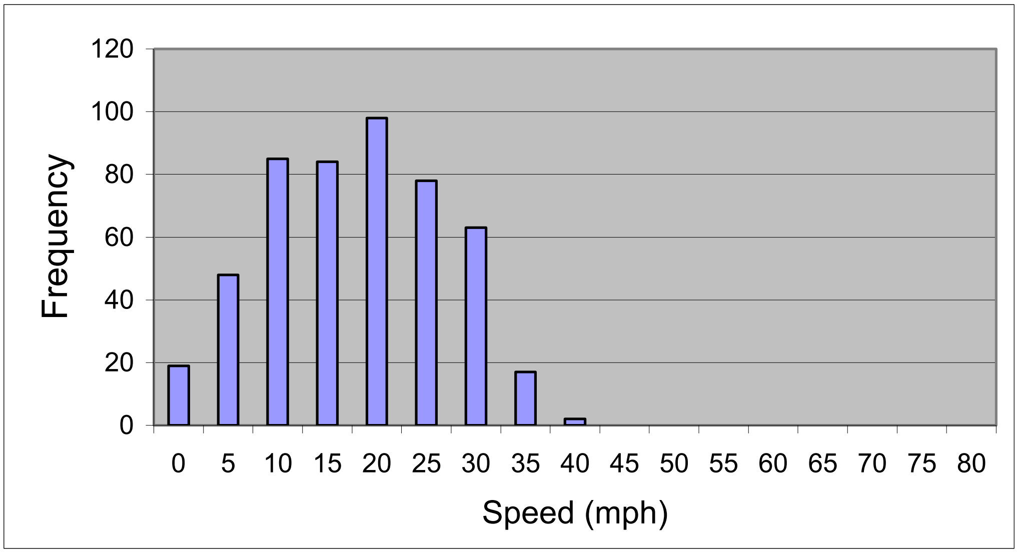

Figure 3-6: Speed distribution on the open lane (Merge point, 10/10/2003)

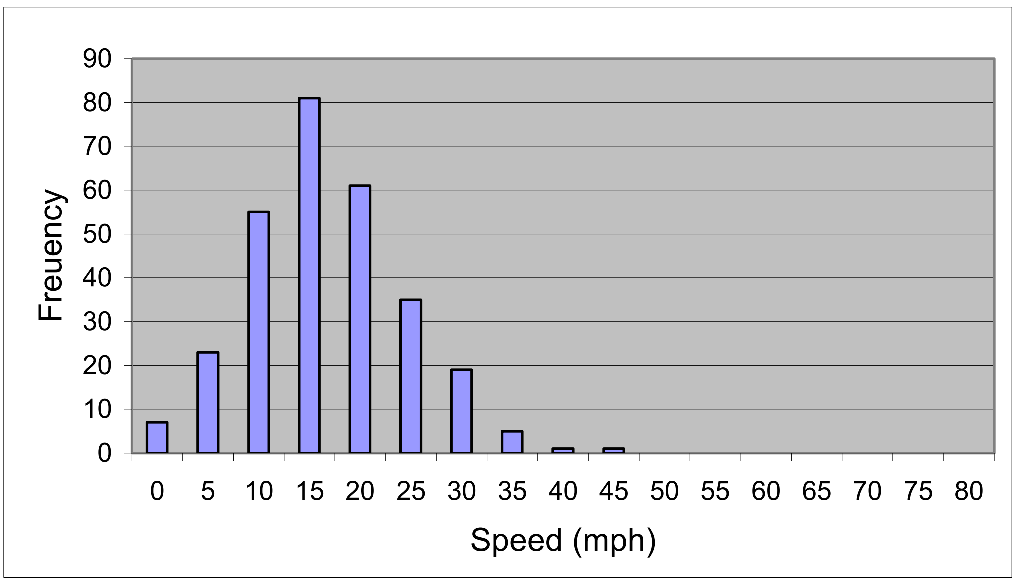

Figure 3-7: Speed distribution on the closed lane (Middle point, 10/10/2003)

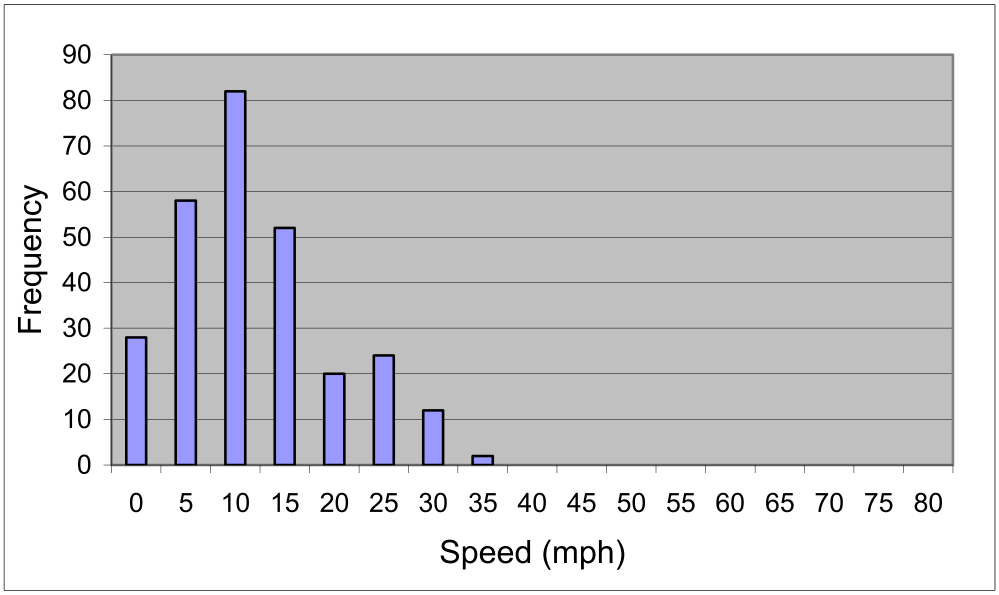

Figure 3-8: Speed distribution on the open lane (Middle point, 10/10/2003)

Based on the speed distributions measured under No-control (i.e., Figures 3-5 to 3-8) and field observations, it is apparent that the RTMS sensors under DLM control did not provide accurate speed measurements (Figures 3-9 to 3-12). For example, it is unlikely that some speeds have exceeded 100 mph on the open lane at the merge point (see Figure 3-10), during the DLM control period.

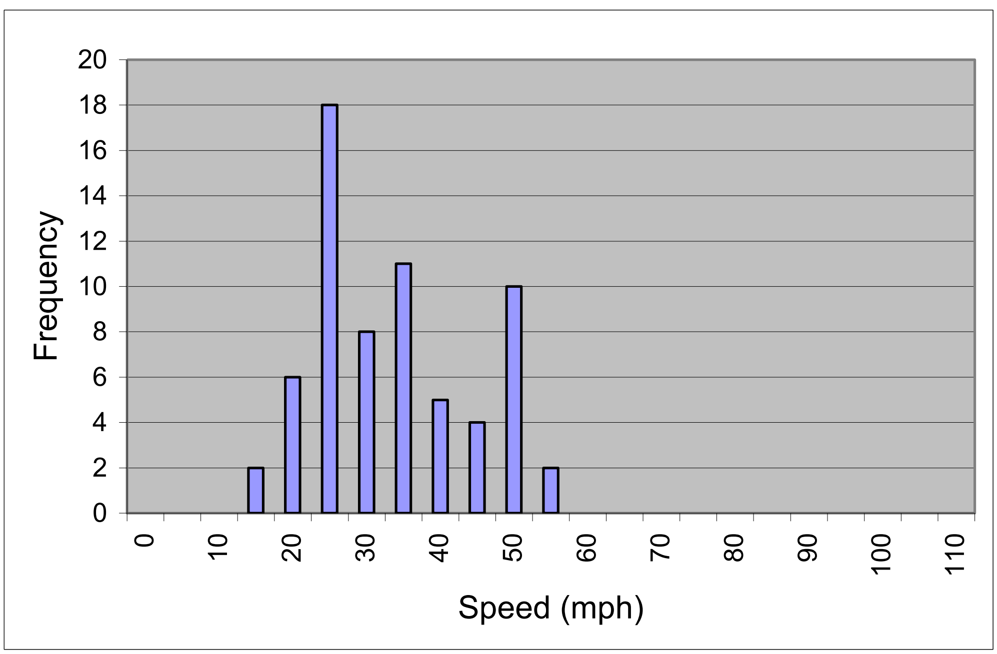

Figure 3-9: Speed distribution on the closed lane (Merge point, 10/23/2003)

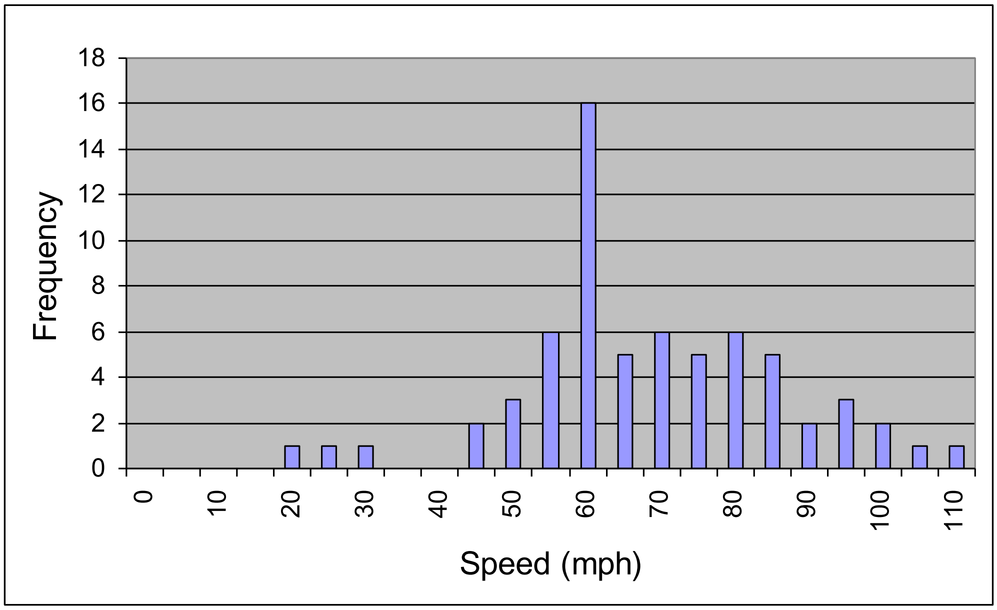

Figure 3-10: Speed distribution on the open lane (Merge point, 10/23/2003)

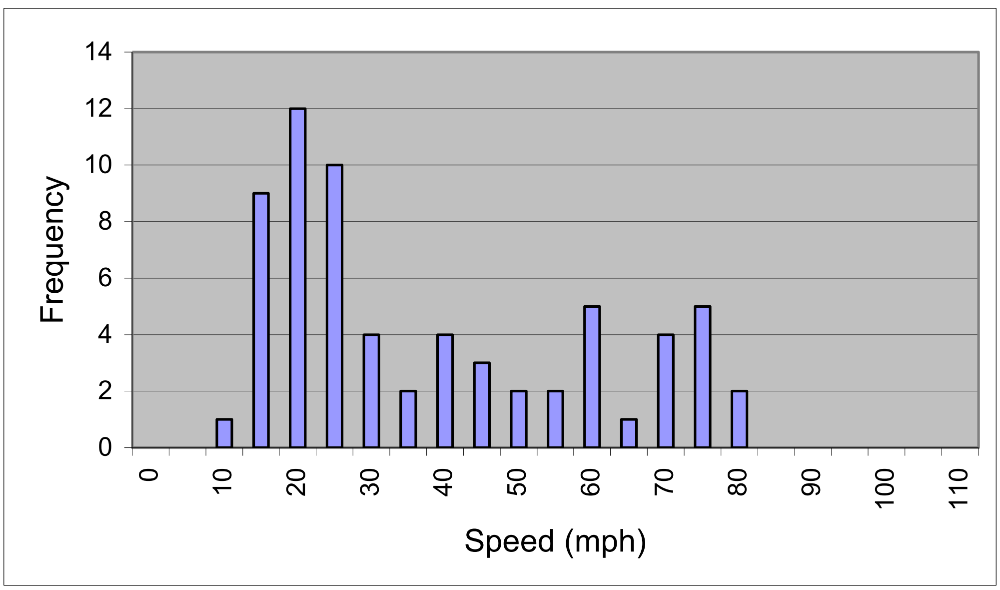

Figure 3-11: Speed distribution on the closed lane (Middle point, 10/23/2003)

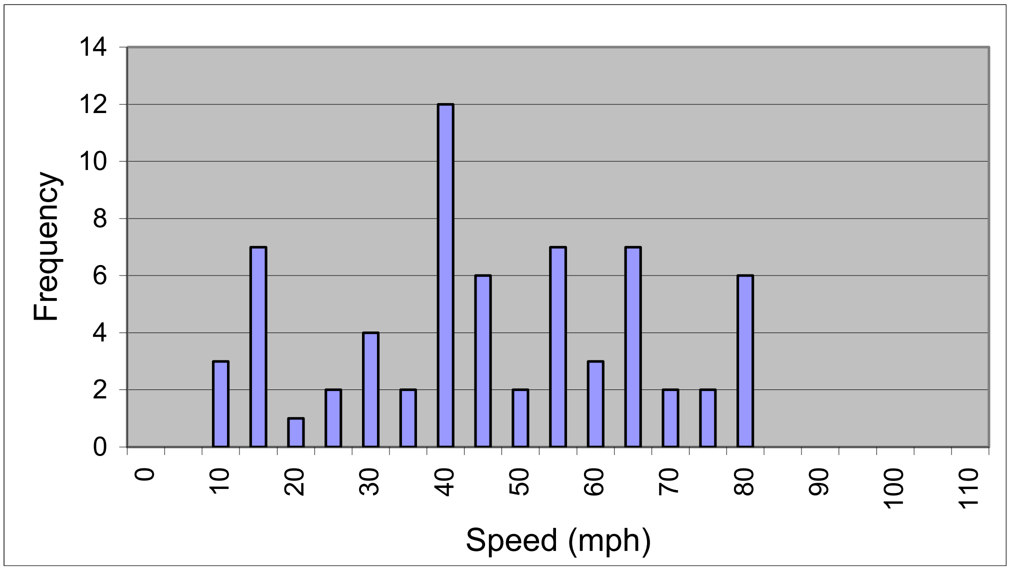

Figure 3-12: Speed distribution on the open lane (Middle point, 10/23/2003)

For comparison, Table 3-2 summarizes the average speed on the closed and open lanes for each sample date. It is clear that the average speed obtained by RTMS far exceeds the speed measured with speed guns. Some of the average speeds even reach 70 mph, which is unrealistic in the congested work zone.

Table 3-2: Comparison of average speeds (unit: mph)

10/10/2003		
Location	Speed gun data	
	Open lane	Closed lane
Merge point	22	24
Middle point	21	26
10/22/2003		
Location	Sensor data	
	Open lane	Closed lane
Merge point	27	56
Middle point	44	57
10/23/2003		
Location	Sensor data	
	Open lane	Closed lane
Merge point	36	70
Middle point	48	40
11/07/2003		
Location	Sensor data	
	Open lane	Closed lane
Merge point	38	71
Middle point	28	41

4. System Performance Evaluation

4.1 Measures of effectiveness (MOE)

The following measures of effectiveness (MOE) were used in the performance evaluation of the deployed DLM system:

- Work zone throughput – The work zone under DLM control is expected to have a higher throughput than that under the No-control;
- Lane volume distribution – The work zone under DLM control is expected to have an approximately uniform distribution of volumes between the open and closed lanes;
- Maximum queue length – The work zone under DLM control is expected to reduce its maximum queue length.

4.2 Evaluation methods

Due to the reliability and accuracy concerns of RTMS data, this study employs the following two methods for performance evaluation of the DLM system:

- Manual analysis from video tapes – It was used in computing work zone throughputs and lane distributions under the No-control and DLM control scenarios;
- Simulation analysis – This supplemental method was adopted to overcome the limitations that traffic volumes under DLM control were not identical to those under No-control, and camcorders would not always capture the tail of a long queue caused by the work zone operation.

4.3 Work zone throughputs

One of the most direct ways to evaluate the operational efficiency of DLM control is to compare its resulting throughput with that of conventional merge operations (i.e., No-control). The numerical results, as shown in Table 4-1, indicate that under DLM control, work zone throughputs, except in the case on 10/22/2004, are slightly higher than that under No-control.

Table 4-1: Numerical Comparison of the manually counted work zone throughputs

Date	Average throughputs (% of heavy truck)	Increased percentages
10/10/2003 (*)	1340 vph (19.0 %)	Base line
10/22/2003	1469 vph (10.4 %)	9.6 %
10/23/2003	1578 vph (11.4 %)	17.8 %
11/07/2003	1487 vph (15.0 %)	11.0 %
11/10/2003	1432 vph (14.8 %)	6.9 %

Note (*): No-control day

Note that the above comparison by the manually counted data analysis method is valid only under the assumption that traffic volume and composition between the No-control and DLM control are at the same level. However, the actual traffic conditions may vary from day to day, and the work zone throughput can be affected by the percentage of heavy vehicles and the level of upstream volume. To perform the comparison on the same basis, this study employs the simulation method to create a set of traffic conditions identical to those days having DLM control.

To ensure the reliability and quality of the simulated results, it is essential to calibrate the simulation program, CORSIM with field data collected on the No-control day.

Simulation parameters to be calibrated with the observed traffic conditions include:

- Calibration of key simulation parameters to reflect the behavior of the driving population:
  - Rubbernecking factor
  - Car-following sensitivity factor
  - Desired free-flow speed
- Comparison of target traffic conditions:
  - Work zone throughput
  - Average speed at the merge point

Table 4-2 summarizes the simulation results prior to and after the calibration.

Table 4-2: Calibration results for the CORSIM simulation network

Traffic conditions	Manual counted data	Simulation results	
		Before calibration	After calibration
Upstream volume	1875 vph	-	-
Heavy truck percentage	19.0 %	-	-
Average speed at merge point	24.0 mph	46.0 mph	22.6 mph
Work zone throughput	1340 vph	1380 vph	1328 vph

With the well-calibrated simulated work zone, one can then input the actual volume and truck percentage on each day under DLM control to estimate the resulting throughput under the No-control scenario.

Comparisons of the work zone throughputs between the No-control and DLM control on four observation days are shown in Table 4-3. Overall, it seems clear that DLM indeed outperforms the No-control in terms of maximizing throughputs.

Table 4-3: Numerical comparison of work zone throughputs

Date	Manually counted throughput (DLM control)	Simulation throughput (No-control)	Increased percentage
10/22/2003	1469 vph	1375 vph	6.8 %
10/23/2003	1578 vph	1476 vph	6.9 %
11/07/2003	1487 vph	1350 vph	10.1 %
11/10/2003	1432 vph	1290 vph	11.0 %

4.4 Lane volume distribution

Volume distribution between both lanes was used to evaluate drivers' compliance to the DLM messages. Ideally, under DLM control, vehicles are expected to distribute equally in both lanes, especially under congested conditions.

Traffic volumes for each lane were collected at three locations: merge point, middle point (0.5 miles before the taper) and upstream point (1.5 miles before the taper) under both No-control and DLM control.

Figures 4-1 to 4-3 display the lane volume distributions at the merge, middle, and upstream points, respectively, under the No-control operation. Note that although volumes were nearly equal between both lanes at the upstream point (see Figure 4-3), many drivers began to use the open lane when they reached the middle point (see Figure 4-2). Also note that a large number of vehicles were observed on the open lane at the merge point (see Figure 4-1).

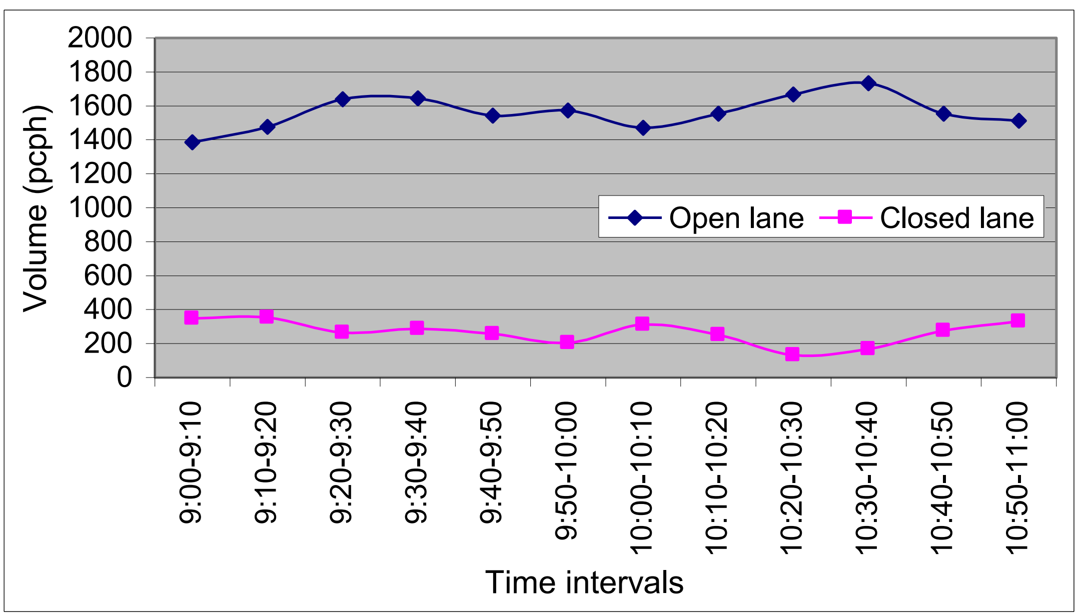

Figure 4-1: Lane volume distribution at the merge point (No-control, 10/10/2004)

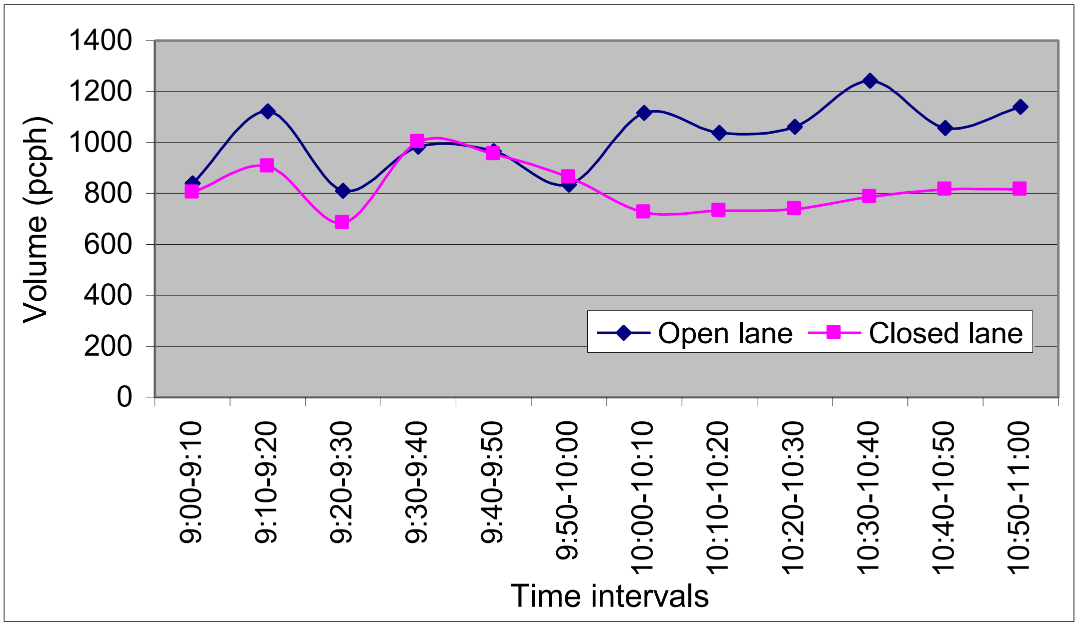

Figure 4-2: Lane volume distribution at the middle point (No-control, 10/10/2004)

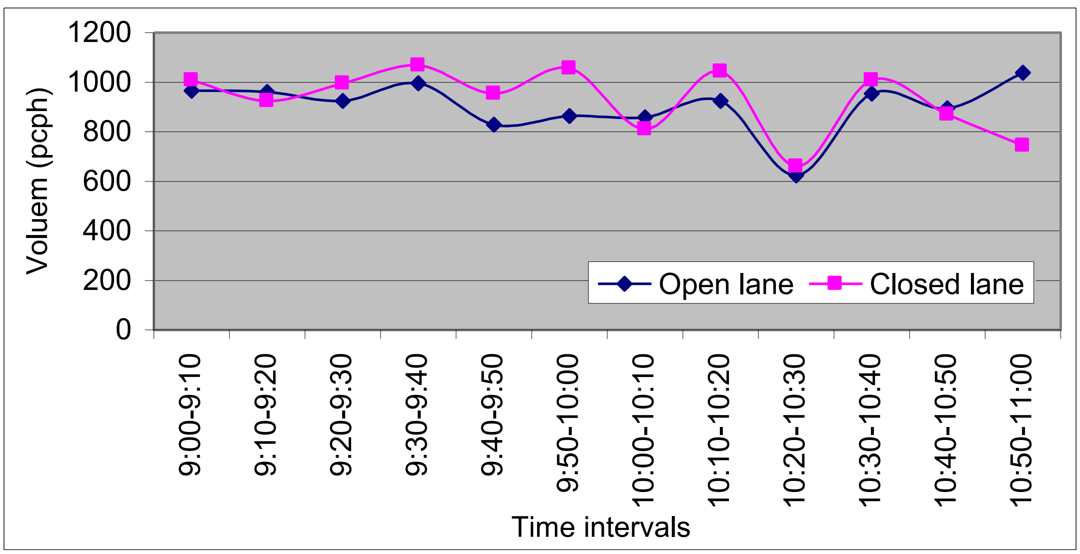

Figure 4-3: Lane volume distribution at the upstream point (No-control, 10/10/2004)

Figures 4-4 to 4-6 illustrate the lane volume distributions at the merge, middle, and upstream points, respectively, under DLM control. Though their patterns are similar to those under the No-control operation, it is notable that the distribution of volume under DLM control between the open and closed lanes at the middle point was quite uniform. This means that drivers indeed followed the messages (i.e., "USE BOTH LANES TO MERGE POINT") displayed on PCMS 3 (see Figure 1-1) when the DLM system was activated under these congested traffic conditions.

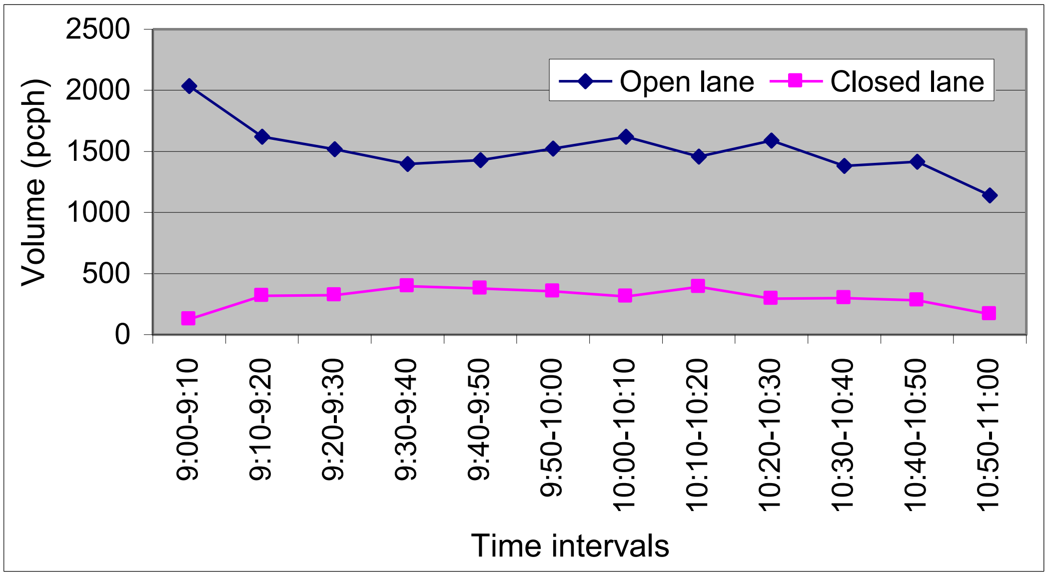

Figure 4-4: Lane volume distribution at the merge point (DLM control, 10/23/2004)

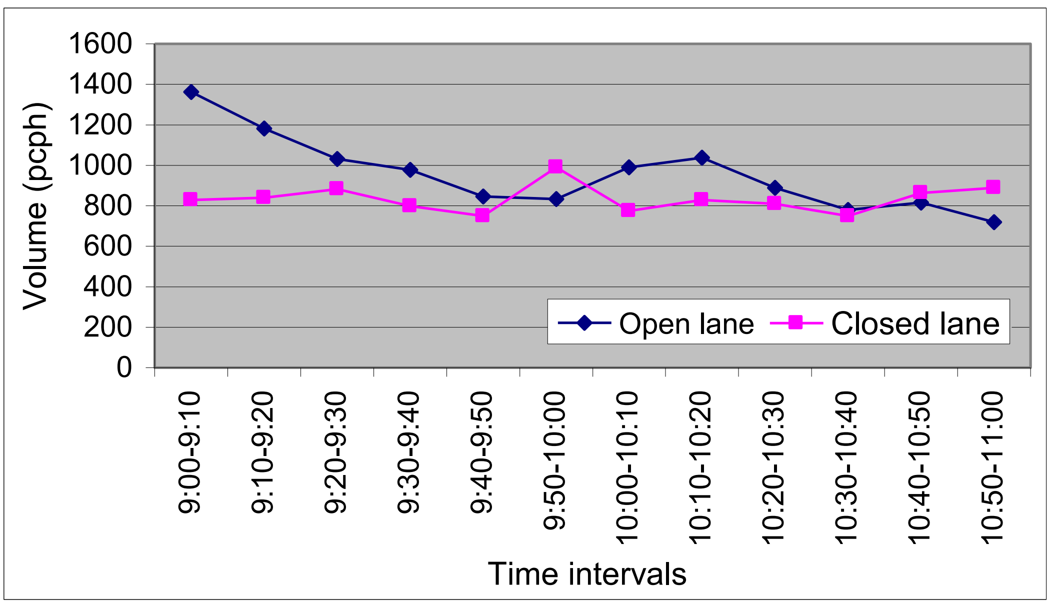

Figure 4-5: Lane volume distribution at the middle point (DLM control, 10/23/2004)

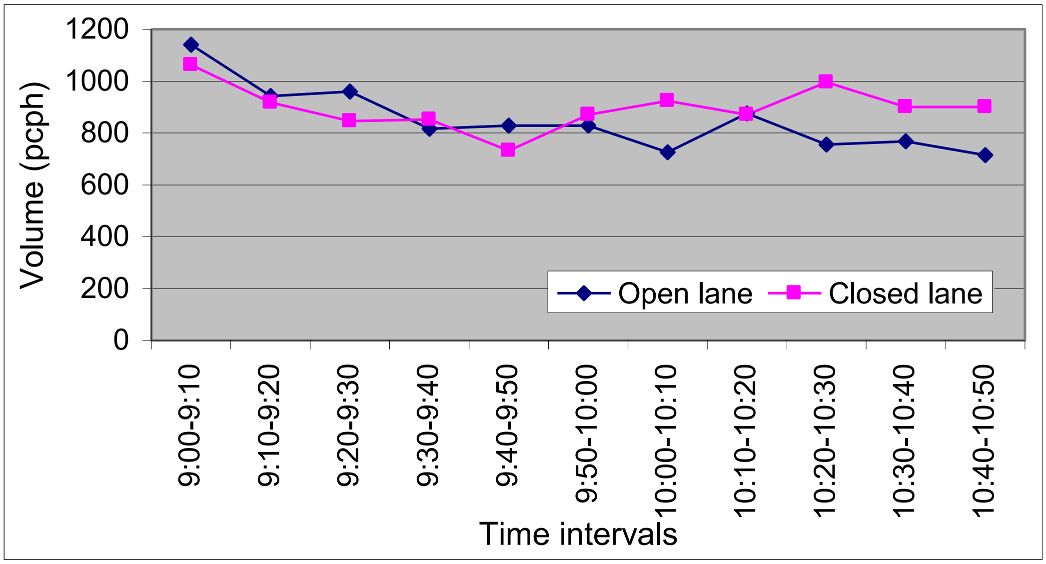

Figure 4-6: Lane volume distribution at the upstream point (DLM control, 10/23/2004)

Table 4-4 shows the differences of volumes counted between the open and closed lanes over the observation days. As evidenced in the differences of the average lane volume distribution, drivers appeared to use both lanes under DLM control, and their compliance rate seemed to increase over time after having more experience (e.g., "USE BOTH LANES TO MERGE POINT").

Table 4-4: Differences in volumes between the open and closed lanes

Date	Merge Point		Middle Point		Upstream Point	
	Avg. difference	Standard deviation	Avg. difference	Standard deviation	Avg. difference	Standard deviation
10/10/2003 *	1297	158	199	168	-26	122
10/22/2003	1207	249	122	200	No data	
10/23/2003	1114	159	17	126	-47	125
11/07/2003	901	208	1	146	-69	136
11/10/2003	932	174	-4	150	-162	143

Note (*): No-control day

However, during field observations, it has been observed that many drivers decided to merge at the locations of the static merge signs (i.e., lane-reduction-symbol and advance lane-closed sign, see BWA 1 and 3 in Figure 1-1) instead of traveling all the way to the first PCMS location. The confusion of these drivers caused by the concurrent presence of the static merge sign and the PCMS message often resulted in multiple merge points along the work zone, and the under utilization of the closed lane.

4.5 Maximum queue length

Due to the discrepancy of traffic volume between the No-control and DLM control days and the limited vision of camcorders, the comparison of maximum queue length was mainly based on the results of the simulation analysis. Table 4-5 shows comparison results of the maximum queue length under No-control and DLM control. Overall, the DLM system appears to substantially reduce the maximum queue length, which is consistent with the fact that it often has relatively uniform volume distribution.

Table 4-5: Comparison of maximum queue lengths between No-Control and DLM control

Dates	Observed queue (DLM control)	Simulated queue (No-control)	Reduced percentages (%)
10/22/2003	1.2 miles	1.3 miles	8.3 %
10/23/2003	1.2 miles	1.4 miles	16.7 %
11/07/2003	1.8 miles	2.0 miles	11.1 %
11/10/2003	0.9 miles	1.2 miles	33.3 %

5. Evaluation of Traffic Safety

5.1 Types of traffic conflicts

To evaluate the impact of DLM on traffic safety, the following four types of conflicts have been measured:

- *Forced merge*: defined as a vehicle on the closed lane attempting to merge into the open lane under an unsafe gap;
- *Lane straddle*: defined as a vehicle straddling along the centerline of the roadway and occupying both lanes;
- *Lane blocking*: defined as two heavy vehicles moving slowly and traveling side-by-side to block both lanes;
- *Stop-and-go*: defined as traffic situations of stop and go maneuvers resulting from traffic conflicts caused by backward and forward shock waves prior to a work zone area.

5.2 Comparison of traffic conflicts

Tables 5-1 and 5-2 summarize the average hourly traffic conflicts incurred at the middle and merge points, respectively. The results indicate that the number of forced merges at the middle point may be decreased under DLM control. At the merge point, however, the number of stop-and-go maneuvers under the No control operation is significantly lower than those under DLM control.

Since the stop-and-go maneuvers may result from the other three traffic conflicts and shockwaves occurring before a merge location, it appears that DLM control may not contribute significantly to improving safety.

Table 5-1: Comparison of traffic conflicts at the middle point

Date	Middle point				
	Forced Merges	Lane Blocking	Lane Straddle	Stop & Go	
				Open lane	Closed lane
10/10/2003 *	17	7	4	24	7
10/22/2003	12	4	6	20	6
10/23/2003	7	1	3	23	8
11/07/2003	10	1	5	26	8
11/10/2003	5	1	3	21	3

Note(*): No-control day

Table 5-2: Comparison of traffic conflicts at the merge point

Date	Merging point				
	Forced Merges	Lane Blocking	Lane Straddle	Stop & Go	
				Open lane	Closed lane
10/10/2003 *	8	3	2	10	2
10/22/2003	9	1	2	21	6
10/23/2003	9	4	3	22	5
11/07/2003	13	6	2	21	10
11/10/2003	8	3	5	18	6

Note(*): No-control day

6. Conclusions

6.1 Conclusions regarding the DLM system evaluation

A properly implemented DLM control in the work zone may contribute to:

- An increase in the overall throughput;
- A reduction in the maximum queue length; and
- A more uniform distribution of volume between lanes.

In contrast, DLM control without placing VMS at proper locations may suffer the following potential problems:

- Increase the number of stop-and-go maneuvers in the work zone; and
- Incur multiple merge locations at the upstream segment of the work zone.

6.2 Observations and recommendations

- Selection of an optimal set of thresholds for system activation
  - The use of only occupancy for system deactivation and activation may not yield the optimal state of work zone operations;
  - Other thresholds should be explored, including a weighted average speed, speed differences between the upstream and merge points, and volume distributions.
  - The critical value of each threshold should not be preset, but determined based on the traffic and environmental conditions.

- Estimation of the potential maximum queue length
  - The last PCMS should be placed at a location over the maximum queue length caused by the lane closures and work zone activities.
  - The location of PCMS #4 in the field test was changed more once due to underestimation of the potential maximum queue length.
  - The maximum queue length can be estimated with field data and simulation analysis.

- Inclusion of speed limit signs
  - The speed limit signs are required for vehicles to merge smoothly from the closed lane into the open lane, and to prevent motorists from experiencing traffic conflicts such as stop-and-go and spillbacks.
  - No warning sign for speed limit in the work zone was used during all field experiments under DLM control.
  - When using static speed limit signs, their locations should be placed in coordination with the PCMS locations.

- Integration with variable speed control to facilitate merging operations
  - The variable speed limit (VSL) control can display optimal speed limits based on real-time detected traffic conditions in advance of the work zone.
  - The VSL control can be the most effective way to enhance DLM performance because it can create a smooth environment for merging maneuvers.

- Locations and spacing between the portable changeable message signs
  - The set of dynamic message signs such as PCMS or VMS should be located based on the perception and reaction times of approaching drivers.
  - The spacing between the PCMS should also be determined based on the approaching average speeds.

- Separation of PCMS system from conventional merging signs
  - Most drivers were observed to face a dilemma incurred by the discrepancy between PCMS messages and conventional static signs as they were mixed within a distance of 0.5 mile in advance of the merge point.
  - For example, the static signs still displayed "RIGHT LANE CLOSED 0.5 MILE" while the PCMS displayed "USE BOTH LANES TO MERGE POINT".

- Placements of PCMS at both right and left sides
  - The PCMS placed at one side (e.g., left side) can be blocked by heavy trucks in the left lane. As a result, vehicles on the right lane and vehicles following trucks on the left lane cannot see the PCMS.

- Improving the resolution of PCMS
  - Drivers at the location of PCMS #3 often weren't able to read the message signs at PCMS #2. Similarly, drivers at the location of PCMS #2 weren't able to see the message displayed at PCMS #1.
  - The top of PCMS needs to be covered with panels so as to minimize the impact of sunlight.

- Improvement of the RTMS sensor accuracy
  - Since both speed and flow rate detected by RTMS sensors for DLM control are not accurate, it is likely that the occupancy measured by RTMS may also be questionable.

6.3 Hardware and vendor evaluations

For the Dynamic Late Merge System provided by International Road Dynamics (IRD) Inc., the SHA engineers have the following observations and comments:

- From the system layout side, SHA noticed that there could be a conflict between the temporary traffic control typical application for a lane closure and the DLM signs. Some drivers would merge at the static W4-2 "Merge Here" symbol sign while others would follow proceed to the Portable Changeable Message Sign (PCMS) with the "Take Your Turn, Merge Here" sign. Also in areas with high truck traffic, it will be beneficial to have at least one location where you have PCMSs on both sides of the highway, reminding motorist to "Use Both Lanes, To Merge Point". This would increase the cost of the system but it will also improve the visibility of the messages to the motorists. Prior to any future deployment of the DLM system, SHA would modify the system layout.

- From the system side, several issues were encountered during the test. This system utilized a cellular modem to communicate between the field devices and the base station. There were times when the system would lose communication because the cell modem was dropped from the cellular network. If the cellular signal was lost, the cell modem would disconnect and would not be able to reconnect. The power to the modem would then have to be cycled in order to reestablish communications. Personnel would have to be dispatched to the site in order to cycle the power. Future systems need to have a better way of reestablishing communications so that personnel do not have to be dispatched.
- The user interface needs to be improved. For future deployments, SHA would like to have the ability to easily modify the thresholds that activate and deactivate the system. In Maryland, since it is very rare that permanent lane closures are set-up, most of the lane closures are for a specified time period. The SHA project engineer or the contractor needs to have the ability to activate the system during lane closure times only. There were instances when the system activated itself due to recurring congestion in the area. SHA also needs to be able to input which lanes are closed either right or left.
- An e-Mail notification or pager-alert feature should be a part of this system. An e-Mail should be sent to a specified list of SHA personnel whenever the system turns on and turns off. This will help with monitoring the system performance and to better troubleshoot problems with the system.
- When using portable cameras, there needs to be enough power supply for the camera to operate through out the deployment. The pan/tilt/zoom feature is a very important for monitoring the traffic through the work zone. One improvement would be to allow SHA to label saved camera positions on the website. This would assist in returning the cameras to key views of the work zones more easily.
- Another issue encountered during the test was that the RTMS sensors were mounted lower than the recommended height above the roadway surface. IRD made some field modifications to increase the sensor height. For future deployments, the trailers provided should allow for multiple mounting heights for the RTMS sensors. The sensors also need to be properly calibrated before the system is deployed. The calibrated sensor data should be checked by SHA prior to starting the system.