MIDWEST SMART WORK ZONE DEPLOYMENT INITIATIVE

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Report Title

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Construction Area Late Merge (CALM) System

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Supplemental Notes

Abstract

The system evaluated comprised 5 VMS, 4 RTMS, 2 microwave traffic sensors, and a laptop-based system control center, all integrated via UHF radio system. The system monitors traffic at each VMS and dynamically changes the messages displayed on the VMS and the operational mode of the system based on traffic conditions downstream of each respective VMS. Three operational modes were defined: early merge, late merge, and incident. Modes were characterized by traffic speeds. Threshold speeds where the system transitioned from one mode to another were based on prior research combined with site characteristics. The test site was an approach to a freeway to freeway interchange reconstruction in Kansas City. When the system was in late merge operation, lane distributions were statistically different than when in early merge operation, but the difference was small. An entrance ramp near the merge appeared to have a very strong effect on driver lane choice, influencing drivers to merge left, even when the system instructed them to hold their lanes. The system performed well (i.e., with few technical difficulties). The results underscored the importance of considering site characteristics very carefully when selecting sites for deployment of dynamic systems and/or late merge systems, and when designing the system deployment configuration.

Project Year 2002 Evaluations

Construction Area Late Merge (CALM) System

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Evaluation Performed by
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INTRODUCTION

Congestion related to work zones is becoming an increasingly high priority among transportation agencies. Of particular concern are high volume work zones. On urban freeways, where volumes tend to be high, applications of Intelligent Transportation Systems (ITS) have opened new doors to congestion reduction. By using wireless communications, several systems have been developed to apply some of those same ITS technologies to highway work zones, where the communications infrastructure is often unavailable.

Simultaneously, states such as Indiana and Pennsylvania have applied a late merge concept to controlling traffic on work zone approaches. The late merge instructs drivers to use all available lanes all the way to the lane drop, and then take turns in the merge process. The conventional merge operation, referred to here as an early merge, encourages drivers to merge from the lane being dropped into the through lanes as early as possible. Under light traffic, early merging will allow for smoother flow. However, under heavier traffic, a late merge may be able to and improve the efficiency of the merge operation. It can also reduce the queue length by more fully utilizing the highway's storage capacity. With early merge operation, when queue lengths are significant, vehicles sometimes use the vacant lane to advance to the front of the queue. Such behavior can contribute to road rage and hinder the smooth flow of vehicles through the lane drop. A late merge precludes this type of behavior.

Research related to late merge operation is relatively sparse, but there is some published work available. Late merge control has been cited as a potential mitigative measure for road rage. (Walters and Cooner, 2001) Simulation studies of late merge operations have been conducted by Nemeth and Rouphail (1982) and by Mousa et al (1990). While Nemeth and Rouphail found that early merge control reduced the instance of forced merges, Mousa's work concluded that it also resulted in greater travel times through the work zone, and could encourage drivers to pass slower vehicles by using the lane being closed. A study of late merge operations in Pennsylvania found an increase in the capacity of the merge operation of up to 15 percent. (Orth-Rodgers & Associates, Inc., 1995) Pesti et al (1999) found that driver compliance with late merge traffic control was lower than expected, possibly reducing the potential advantages of the technique. As part of the Midwest Smart Work Zone Deployment Initiative (MwSWZDI), McCoy and Pesti (2001) introduced the dynamic late merge concept in which a system of VMS and real time traffic sensors provide conventional (early) merge traffic control during uncongested conditions, and transition to late merge traffic control when congestion occurs. They were not able to conduct a test of their proposed system.

Partly as a followup to McCoy and Pesti's study, this study was initiated to investigate the effectiveness of dynamic late merge operations on a freeway work zone approach. The Construction Area Late Merge (CALM) system from The Scientex Corporation is a dynamic merge system configured to operate as an early merge system under light traffic loads and as a late merge system under heavier traffic loads.

Goals

The two primary goals of this evaluation were to compare the effectiveness of the CALM system (late merge) with that of conventional work zone traffic control (early merge) and to collect data that might be used later to improve the modeling of late merge systems. Secondary goals included studying the effects of displaying real-time downstream speeds and examining system deployment and operation considerations.

TECHNOLOGY DESCRIPTION

CALM comprises three essential components. The core of the system is the Central System Controller (CSC), a computer running the custom software package provided by Scientex and connected to the field components via some means of serial communication. In this deployment, a laptop computer was used for the CSC as shown in Figure 1, and 900 MHz radio was used for the communications link between the CSC and the field components. This necessitated direct line of sight from each field component to either the CSC or to another field component that could serve as a relay station. The CSC was connected to a data modem (shown in Figure 2), which was connected to an antenna mounted atop a 40-ft pole.

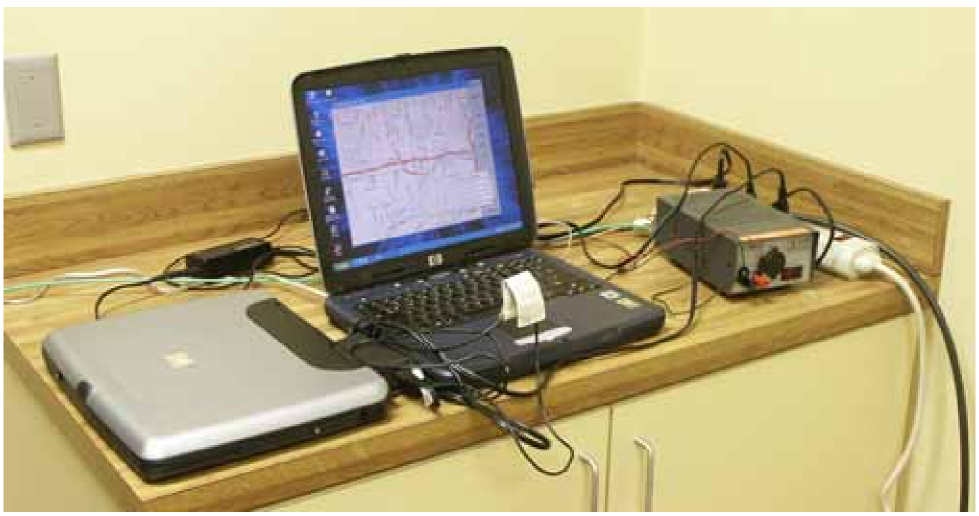


Figure 1. Central System Controller (CSC) for test application.

The field components in this configuration comprised five trailer-mounted variable message signs (VMS) and two trailer-mounted Remote Traffic Microwave Sensors (RTMS). One of the VMS is shown in Figure 3. Four of the five VMS trailers also housed a radar speed sensor. The radar sensors provided overall (i.e., not lane specific) speeds and volumes, which were used in system operation as well as for data analysis. The RTMS sensors were operated in a sidefire orientation, reporting lane-specific speeds and volumes. Sidefire RTMS can report exaggerated volumes and invalid speeds under very congested conditions (e.g., when speeds are lower than 15-20 mph), but this was the most effective means of obtaining lane specific data in this case. The data collected by the RTMS sensors were needed to evaluate the system. They are not generally used in CALM implementations, and in this study were only used to log data. That is, the data they collected was not used for system operation, but simply recorded for post-analysis. The VMS were provided by VERMAC.

Figure 2. Data modem used by CSC to communication with field components.

Figure 3. Variable Message Sign 1 (VMS1) in Late Merge Mode.

For identification purposes, the VMS were numbered from the merge point, beginning with 1 as shown in Figure 4. The single board on the inside shoulder was designated VMS 0 to maintain continuity of the sensor IDs, which were integrated with VMS 1 through VMS 4 but not VMS 0.

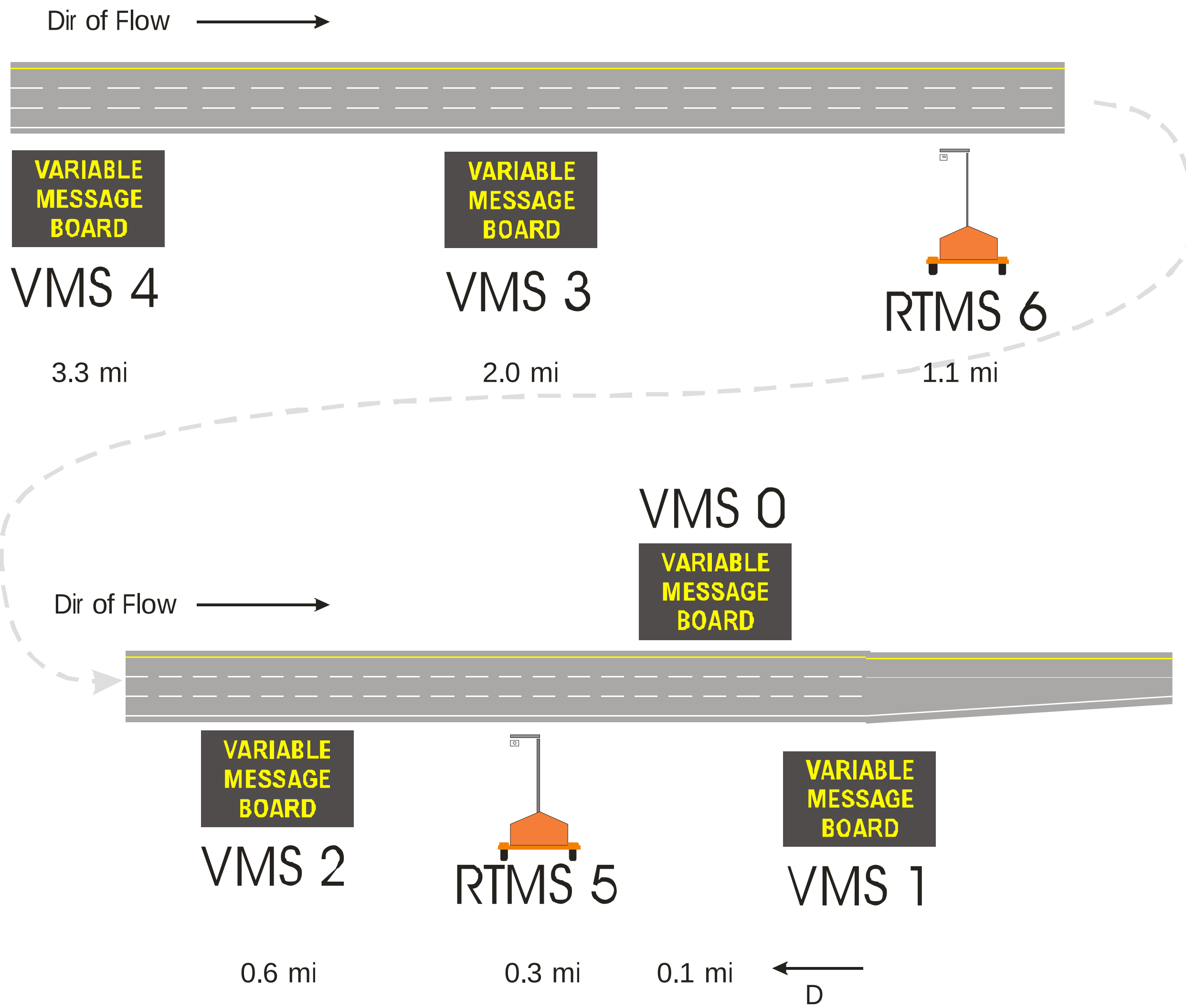


Figure 4. CALM System field components.

The maximum number of field components that can be integrated with the system is dependant upon the communications component. The communication media and implementation employed establishes the communications bandwidth (i.e., the amount of data that can be transferred in a given time period). Once the bandwidth is established, the number of components is a function of the data elements to be transmitted and the frequency of transmission. In this study, for example, field components reported not only volumes and mean speeds for each time period, but also the sum of the speeds and the sum of the squares of the speeds, both of which are parameters used in the statistical analysis during post processing, but which are not used in the real time operation of the system. Additionally, during this study the system was set to report data in 4-minute increments, which is a smaller time period that would typically be used. The RTMS also occupied bandwidth, although they were not involved in system operation, but only collected data for post processing.

System Operation

Because the implementation of the CALM system used in this study was somewhat novel in that it was intended to switch automatically between operational modes, the operational scheme—what messages get displayed on which VMS and when—had to be developed from scratch. The scheme used was developed specifically for this study by The University of Kansas in cooperation with KDOT and Scientex. Other deployment contexts and configurations may dictate a different scheme.

The system was configured to operate in one of three modes—Early Merge, Late Merge, or Incident—switching automatically from one mode to another based on current traffic conditions as indicated by prevailing speeds. Incident Mode is a special case of late merge operation that was triggered when speeds are exceptionally low.

Based on both the system mode and the speeds near each VMS, the system will operate each VMS in one of five VMS states—Early Merge, Late Merge-A, Late Merge-B, Incident-A, or Incident-B. In general, the system operation mode reflects the lowest speeds being reported by any of the system sensors. The operational state of each VMS reflects the prevailing speeds at the next VMS downstream and determines what specific message will be displayed.

Mode Transitions

Transitions between modes are based on average operating speeds. Speeds are categorized as Level 1, Level 2, or Level 3. The determination of the speed ranges corresponding to each level is discussed in Operational Mode Thresholds (see pg. 17). The speeds *do* relate to the operating modes, but there is *not* a one to one correlation between speed levels and operating modes. For example, a particular sign may observe Level 1 speeds, but the entire system may still be in Late Merge (or even Incident) mode because of lower speeds at a different (esp. downstream) location. Speed categories and VMS modes are associated with a specific location, while system modes are associated with the system as a whole. The speed categories are defined in Table 1. The categories overlap to help prevent the system from oscillating between modes when speeds are near the transition point. The choice of 5 mph as the range overlap was arbitrary. The same values define the transitions between speed categories, as shown in Table 2.

Table 1. Operating Speed Categories

Level	Speed Range (Lane 2)	Speed Range (3-lane average)
1	>35 mph	> 46 mph
2	15 to 40 mph	15 to 51 mph
3	0 to 20 mph	0 to 20 mph

Table 2. Speed Category Transition Points

From	To	At
Level 1	**Level 2**	46
Level 2	**Level 1**	51
Level 2	**Level 3**	15
Level 3	**Level 2**	20

Some systems have included time stamps in their messages to affirm the timeliness (and thus the importance) of the message. The Kansas DOT only uses VMS when there is information to present that does not duplicate the static signing. Consequently, it was felt that the public has an understanding that any message displayed on a VMS is important, and time stamps were unnecessary. Each sign can be one of 5 states—one state for early merge mode and two states each for late merge mode and incident mode, the state reflecting whether or not the queue extends to that sign. A sign being in *Mode X-A* indicates the queue *does not* extend to that sign (rather, it doesn't extend past the next downstream sign). A sign being in *Mode X-B* indicates that the queue *does* extend to that sign. Here, "queue" is defined as Level 2 or Level 3 operating speeds. Sign states are described in terms of speed categories in Table 3.

Table 3. System Operating Mode Definitions

State	**Description/Criteria**
Early Merge	All sensors report speed Level 1.
Late Merge-A	Next sensor (i.e., sensor immediately downstream of VMS) reports speed Level 1; at least one other sensor reports speed Level 2; no sensors report speed Level 3.
Late Merge-B	Next sensor reports speed Level 2; no sensors report speed Level 3.
Incident-A	Next sensor reports speed Level 1; at least one sensor reports speed Level 3.
Incident-B	Next sensor reports speed Level 2 or Level 3; at least one sensor reports speed Level 3.

The literature does not provide any previous examples of dynamic merge systems configured to switch between early and late merge operational modes based on traffic conditions. As yet unpublished simulation work has been conducted at the University of Nebraska by Geza Pesti (now at the Texas Transportation Institute). This work was also funded by the Midwest Smart Work Zone Deployment Initiative (MwSWZDI). Its intent was to examine the relative effectiveness of early and late merge operations at various traffic volumes. This work was utilized in determining the transition thresholds for the study configuration, as is discussed later in this report. The specific messages used are listed in Table 4 and all the states for each VMS are shown in Table 5.

Table 4. System messages used.

VMS ID	State	Message, Page 1	Message, Page 2
0-2	Early Merge		
3-4	Early Merge	CURRENT AVERAGE SPEED	54 MPH 1 MILE AHEAD
1	Late Merge-A or -B Incident-A or -B	TAKE YOUR TURN	MERGE HERE
0	Late Merge-A Incident-A		
2	Late Merge-A	CURRENT AVERAGE SPEED	36 MPH AHEAD
3-4	Late Merge-A	CURRENT AVERAGE SPEED	42 MPH 1 MILE AHEAD
0, 2-4	Late Merge-B Incident-B (Do not use page 2 for signs downstream of static “DO NOT PASS” sign)	USE ALL LANES TO MERGE	DO NOT PASS
2-4	Incident-A	STOPPED TRAFFIC AHEAD	SLOW DOWN

Table 5. System Operation Message Table.

VMS ID	Early Merge	Late Merge-A	Late Merge-B	Incident-A	Incident-B
0			USE ALL LANES TO MERGE		USE ALL LANES TO MERGE
1		TAKE YOUR TURN MERGE HERE	TAKE YOUR TURN MERGE HERE	TAKE YOUR TURN MERGE HERE	TAKE YOUR TURN MERGE HERE
2		CURRENT AVERAGE SPEED 36 MPH AHEAD	USE ALL LANES TO MERGE	STOPPED TRAFFIC AHEAD SLOW DOWN	USE ALL LANES TO MERGE
3	CURRENT AVERAGE SPEED 54 MPH 1 MILE AHEAD	CURRENT AVERAGE SPEED 42 MPH 1 MILE AHEAD	USE ALL LANES TO MERGE DO NOT PASS	STOPPED TRAFFIC AHEAD SLOW DOWN	USE ALL LANES TO MERGE DO NOT PASS
4	CURRENT AVERAGE SPEED 54 MPH 1 MILE AHEAD	CURRENT AVERAGE SPEED 42 MPH 1 MILE AHEAD	USE ALL LANES TO MERGE DO NOT PASS	STOPPED TRAFFIC AHEAD SLOW DOWN	USE ALL LANES TO MERGE DO NOT PASS

STUDY SITE

The site used for this evaluation was selected from a handful of sites recommended by the Kansas DOT as those most likely to consistently experience queuing due to construction activities during Spring 2003. Final site selection was based on several factors, including the likelihood of queuing, the schedule and duration of the construction, the stability of the work zone configuration, upstream geometry (e.g., shoulders to accommodate trailer-mounted signs, no interchanges with major freeways, and identification of a suitable site for the Central System Controller (CSC)).

From the recommended potential sites, the site selected for the study was a segment of I-70 Eastbound in Kansas City, Kansas. A major reconstruction of the interchange between I-70 and I-635 required the closure of one lane eastbound throughout the construction period. Ramps between the Interstates were closed. Standard work zone traffic control was present, in addition to the CALM components. The AADT ranged from 45,400 vpd (T=14%) at the western end of the segment to 71,300 vpd at the eastern end of the segment (T=11%). (KDOT, 2003) There are three lanes on the approach and two lanes through the work zone. The configuration of the work zone with respect to this approach was not expected to change significantly during the construction period, which was anticipated to be 6 months or more (the planned duration of the evaluation was 4 weeks).

Figure 5 shows a plan view of the study segment, including system field components and pertinent entrances, exits, and traffic control. The CSC was located at a Kansas Department of Transportation (KDOT) facility (formerly a rest area) located just off the westbound lanes between VMS 3 and VMS 4. Figure 6 shows a photograph of the lane drop and the field components located immediately upstream. Note the entrance ramp of the 57th St. interchange, which proved to play an important role in the operation and evaluation of the system.

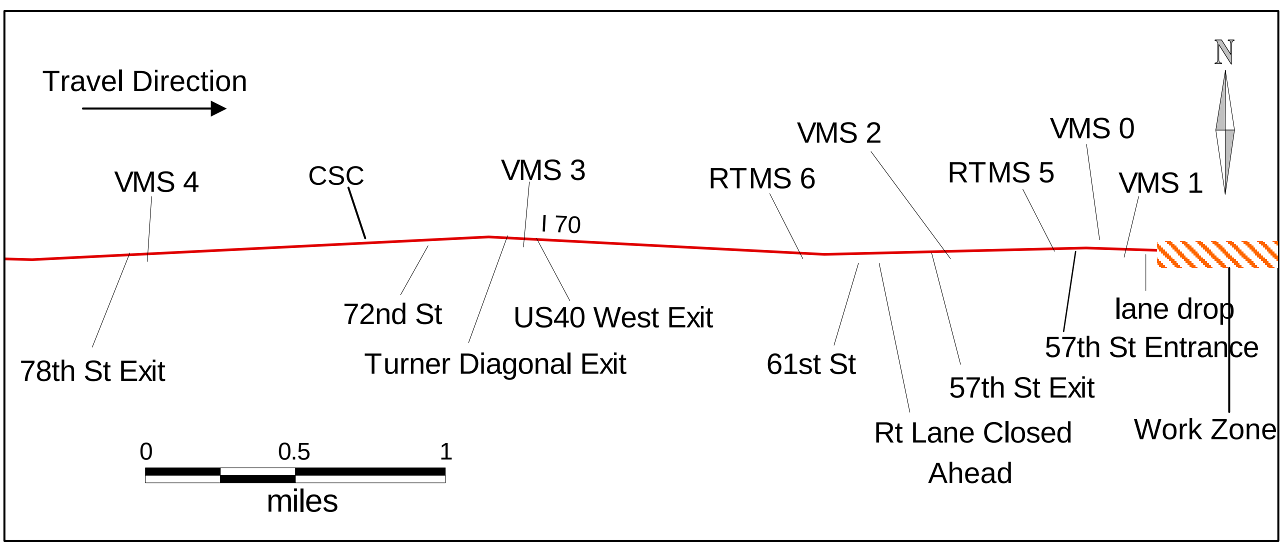


Figure 5. Plan view of study segment.

Figure 6. End of Work Zone Approach

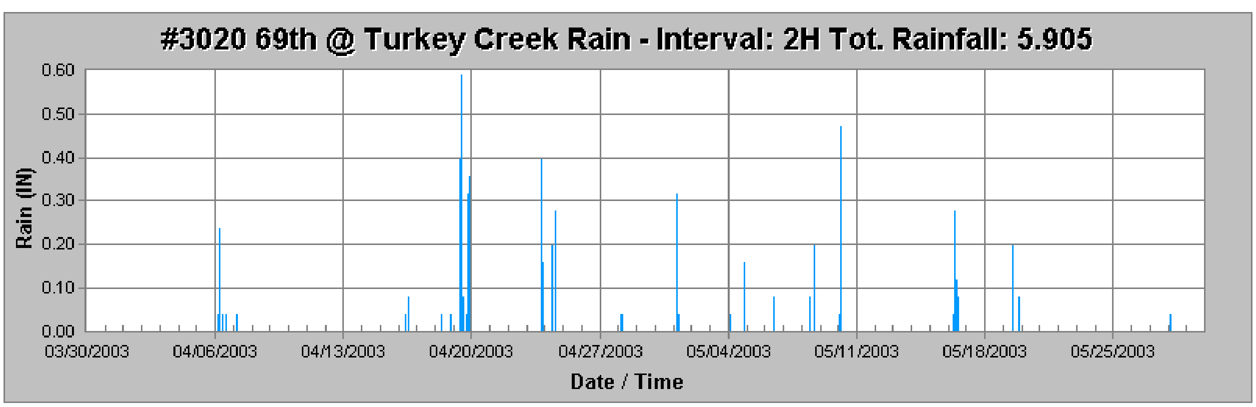
DATA COLLECTION

Data collection began on March 31, 2003. The initial week was spent testing the system operation and verifying the accuracy of the speed sensors (by comparison with a laser speed gun). The deployment was initially planned for just 4 weeks, so the before data was limited to one week. The deployment was later extended to 6 weeks. Data analysis was conducted for the periods shown in Table 6. Data was collected continuously, but for analysis purposes, only congestion data was of interest. Additionally, recurring congestion was more useful than incident-induced congestion. For this reason, only weekdays were considered in the analysis, and corresponding dates are shown in the table.

Table 6. Study duration and key dates.

Phase	Start Date	End Date
Testing	3/31/03	4/4/03
Before (baseline)	4/8/03	4/11/03
After, Week 1	4/14/03	4/18/03
After, Week 2	4/21/03	4/25/03
Overall Deployment	3/30/03	5/6/03

The morning peak period was taken to be between 7:00 AM and 9:00 AM. Rain occurred during the peak period for only two of the days during the study period. On April 6, 0.04 in of rain was recorded at 7:01 AM. On May 16, 0.04 in were logged at 7:50 AM and again at 8:56 AM. In both cases, the rainfall magnitude was very small, and was ignored in the data analysis. Figure 7 shows the continuous rainfall history during the study period.



Source: City of Overland Park, Kansas (www.stormwatch.com)

Figure 7. Rainfall history approximately 8 mi south of the study site.

During data collection, there were four difficulties encountered that resulted in loss of data, but only two of which had broader implications.

1. Throughout the test, retrieving data through the telephone access line proved difficult. The connection was terminated prematurely or the system failed to connect at all. No conclusion could be reached as to whether this problem was due to the phone system, the computer modem, or the connection software (PC Anywhere 9.0), although the phone system is suspected to be the cause of the problem. The modem and software have been used successfully elsewhere. Scientex asserted that this problem has not occurred in other installations. This line was only used to remotely retrieve data that had already been logged by the CSC, and its incapacitation had no effect on the CALM system operation, except that identifying system operation errors could not be done without a site visit. Data logs could still be retrieved at the computer. All internal system communication was done through a wireless radio modem, not through the public telephone system, and was unaffected by this difficulty.

2. On April 25, all system communications were down. The cause was discovered to be a disconnect in the wiring at the CSC. Someone had inadvertently disconnected the radio modem from the computer and had not properly restored the connection. Once the connection was properly plugged in, system communications returned to normal.

3. VMS 3 failed twice during the test, once on April 13 and again on April 20. The latter failure was not detected until April 25 because of the difficulty encountered in checking the data remotely, as described above. In both cases, it appears that the sensor malfunctioned, and the system continued to repeat the sensors last valid reading until the unit was reset (i.e., powered down and back up). The unit manufacturer, VERMAC, volunteered to replace the unit, but no further difficulties were encountered, so replacement did not become necessary.

4. Both RTMS sensors failed during the weekend of May 3. It was determined that the cause of the failure was the battery power supply, and since the critical data collection was complete, the units were not replaced. The RTMS have lower power consumption than the VMS, but they typically also have fewer batteries. The batteries were not monitored during the test, so this type of failure could be easily averted in practice.

It should also be noted that VMS 0 was hit by a vehicle the morning of May 12. It was not replaced, because the critical data collection was complete. VMS 0 was located on the inside shoulder.

The history of the study period with respect to component operation is shown in Table 7. Shaded cells are those days for which the data collected was usable for analysis. Note that shaded cells do not indicate proper system operation. For example, weekend days were not used in the analysis because of their unique traffic characteristics. In most cases, system operation was normal.

Table 7. Log of Operational History by Component.

Day	Date	Phase	VMS1	VMS2	VMS3	VMS4	RTMS5	RTMS6
	03-30-2003	testing	testing	testing	testing	testing	testing	testing
Mon	03-31-2003	testing	testing	testing	testing	testing	testing	testing
Tue	04-01-2003	testing	testing	testing	testing	testing	testing	testing
Wed	04-02-2003	testing	testing	testing	testing	testing	testing	testing
Thu	04-03-2003	testing	testing	testing	testing	testing	testing	testing
Fri	04-04-2003	testing	testing	testing	testing	testing	testing	testing
	04-05-2003	testing	weekend	weekend	weekend	weekend	weekend	weekend
	04-06-2003	testing	weekend	weekend	weekend	weekend	weekend	weekend
Mon	04-07-2003	testing	testing	testing	testing	testing	testing	testing
Tue	04-08-2003	baseline	never slow					
Wed	04-09-2003	baseline						
Thu	04-10-2003	baseline						
Fri	04-11-2003	baseline	slow all day--lane closed in work zone?					
	04-12-2003	baseline	weekend	weekend	weekend	weekend	weekend	weekend
	04-13-2003	baseline	weekend	weekend	weekend	weekend	weekend	weekend
Mon	04-14-2003	after						
Tue	04-15-2003	after			down			
Wed	04-16-2003	after	raining					
Thu	04-17-2003	after	never slow					
Fri	04-18-2003	after	never slow					
	04-19-2003	after	weekend	weekend	weekend	weekend	weekend	weekend
	04-20-2003	after	weekend	weekend	weekend	weekend	weekend	weekend
Mon	04-21-2003	after			down			
Tue	04-22-2003	after			down			
Wed	04-23-2003	after			down			
Thu	04-24-2003	after	incident	incident	down	incident	incident	incident
Fri	04-25-2003	after	comms error	comms error	comms error	comms error	comms error	comms error
	04-26-2003	after	weekend	weekend	weekend	weekend	weekend	weekend
	04-27-2003	after	weekend	weekend	weekend	weekend	weekend	weekend
Mon	04-28-2003	after						
Tue	04-29-2003	after						
Wed	04-30-2003	after						
Thu	05-01-2003	after						
Fri	05-02-2003	after						
	05-03-2003	after	weekend	weekend	weekend	weekend	weekend	weekend
	05-04-2003	after	weekend	weekend	weekend	weekend	weekend	weekend
Mon	05-05-2003	after						down
Tue	05-06-2003	after					down	down
Wed	05-07-2003	after					down	down
Thu	05-08-2003	after					down	down
Fri	05-09-2003	after					down	down
	05-10-2003	after	weekend	weekend	weekend	weekend	weekend	weekend
	05-11-2003	after	weekend	weekend	weekend	weekend	weekend	weekend
Mon	05-12-2003	after	VMS0 down				down	down
Tue	05-13-2003	after	VMS0 down				down	down
Wed	05-14-2003	after	VMS0 down				down	down

DATA ANALYSIS

Data analysis comprised two separate tasks. First, a preliminary analysis was conducted to establish the thresholds for changing from early merge to late merge operation, and vice versa. Second, the before data was compared with the after data to identify any effects of the system on traffic characteristics.

Operational Mode Thresholds

Little documented research has been conducted on dynamic late merge systems, and no precedent existed for a system such as that evaluated in this study. In particular, this system transitioned dynamically from early merge operation to late merge operation, based on current traffic conditions detected by the system, and the lane being dropped was the outer of three lanes, rather than two, as has been the case with many previous late merge evaluations.

At any given time, the system operated in one of three modes—Early Merge, Late Merge, or Incident—based on the speed category reported by each sensor. Speeds are categorized as Level 1, Level 2, or Level 3, all of which are defined in Table 8 (repeated from Table 1 for convenience). The categories overlap to help prevent the system from oscillating between modes when speeds are near the transition point.

Table 8. Operating Speed Categories

Level	Speed Range (Lane 2)	Speed Range (3-lane average)
1	>35 mph	> 46 mph
2	15 to 40 mph	15 to 51 mph
3	0 to 20 mph	0 to 20 mph

There are four possible transitions, each with a threshold speed at which the transition will occur. Geza Pesti, formerly of the University of Nebraska, has performed simulations to explore at what point a late-merge mode of operation becomes more efficient than an early merge mode of operation. In correspondence about his preliminary results, he wrote,

> "The MOEs were queue length, flow rate downstream of the lane closure, and delay. Simulations were conducted for a range of traffic volumes (500-1800 vphpl) over a 10-mile long two-lane section with 75 mph speed limit. The two lanes were reduced to one for the last one mile. Both left and right lane closures were considered. We found that the conventional merge control performed better when the average densities were below 45-50 pcphpl, and the average speeds above 35-40 mph over a 1-mile section just upstream of the lane closure, and the late merge control was more effective for densities higher than 50 pcphpl and speeds lower than 35 mph."

He emphasized that the model required additional calibration and validation before the results could be considered more than preliminary. However, at the time, this was the only quantitative analysis available on this subject, so it was used as the basis for threshold speeds in this deployment. Because Pesti's analysis was situation where two lanes merge into one, his results could not be applied directly to this study, since the study site involves three lanes merging into two. Data collected during the testing phase was used to map Pesti's speed thresholds to analogous conditions on the segment under observation in this study.

At this site, Lane 1, the rightmost lane (i.e., outside lane), was dropped, and the traffic merged into Lane 2. It was assumed that lane 3, the inside lane, would be largely unaffected by the lane drop, particularly while volumes were low, and that the effect of the merge would begin to be significant as conditions approach the threshold for entering late merge operation. Based on these assumptions, Lane 3 could be ignored and Pesti's thresholds could be applied to lanes 1 and 2 directly.

Speeds appeared to be a better parameter to use for the thresholds than density (although in retrospect, density appears to be the more appropriate parameter—see below for discussion). Given the minimal effect of the merge on Lane 3 and the fact that the sensors driving the system's operation do not distinguish between lanes, the speeds in Lane 1 would likely skew the overall average speeds relative to the scenario represented in Pesti's simulations. To compensate for this effect, a relationship between speeds in Lane 2 and overall average speeds was developed and applied to the threshold speeds recommended by Pesti. The relationship did not need to be fully developed, but needed only to be defined at the threshold speeds. During the system testing, the lane specific speeds captured by the RTMS sensors were compared with the overall speeds logged by the radar sensors (collocated with VMS) to develop a mapping of speeds in Lane 2 to overall speeds. The data collected by the RTMS during the 4/2/03 morning rush hour are shown in Figure 8 and Figure 9. Missing data points (e.g., 7:02 in Figure 8) are time periods during which speeds were not reported or the reported speeds or volumes were obviously erroneous. The average represents the overall average, or the average of the three lanes weighted by volume.

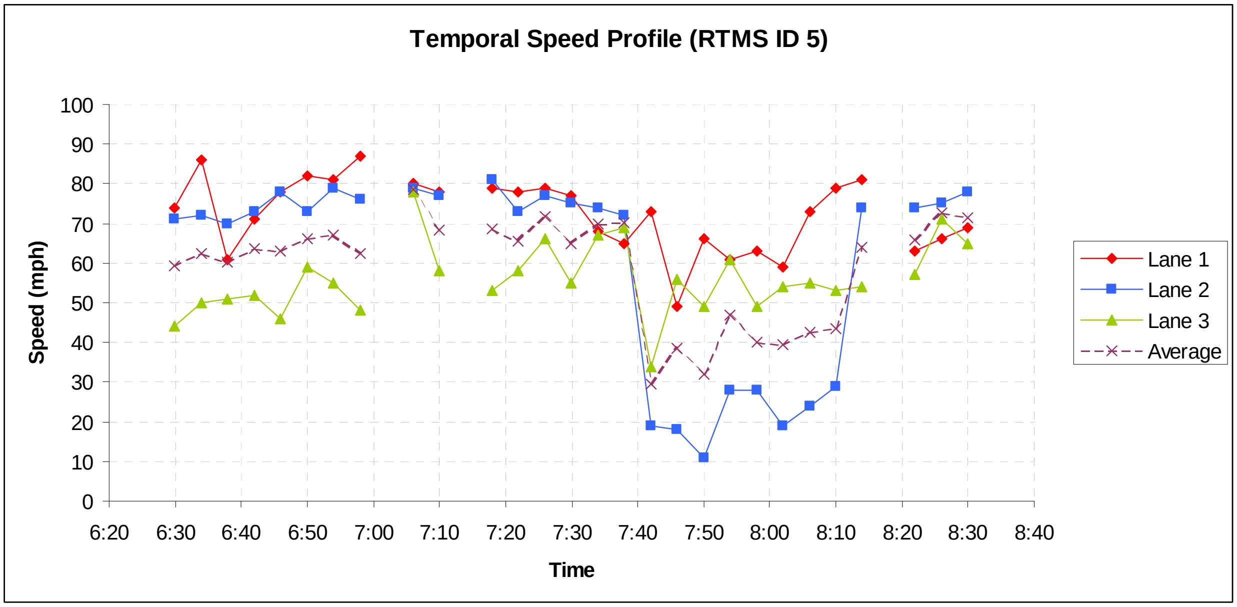


Figure 8. Speed data from RTMS 5 on 4/2/03.

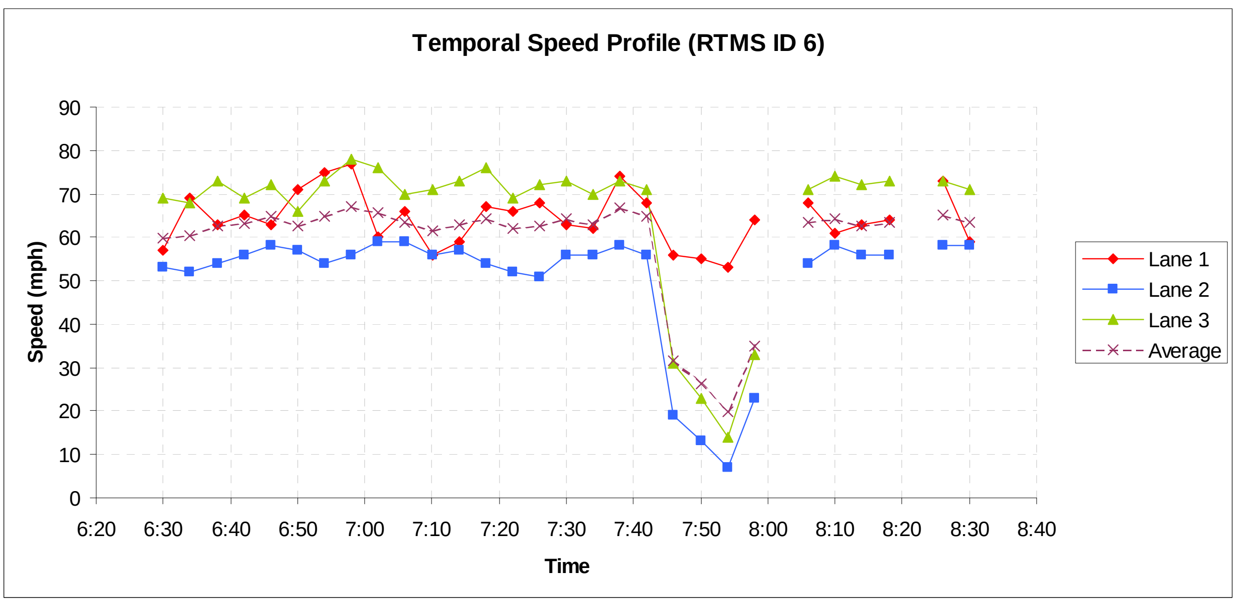


Figure 9. Speed data from RTMS 6 on 4/2/03.

Speed vs. Density for Threshold Parameter

To relate the data collected to the parameter values that resulted from the Pesti study, values averaged across all 3 lanes were compared with the analogous values for Lane 2. Figure 10 and Figure 11 show speeds and densities, respectively, plotted for Lane 2 versus the overall averages across all three lanes for RTMS 5. Figure 12 and Figure 13 show analogous data for RTMS 6.

Both measures for combined lanes appear to be good predictors for the values associated with Lane 2. In both cases, the relationship for speeds has a higher R^2 value, though only by a nominal amount for RTMS 6. Based on this data from the testing week, speed was chosen as the parameter to be used to determine when the system should change operational modes.

In examining the larger volume of data available after the study was completed, it became clear that density would be a more appropriate parameter to use for determining system mode transitions. This issue is discussed more fully later in this report.

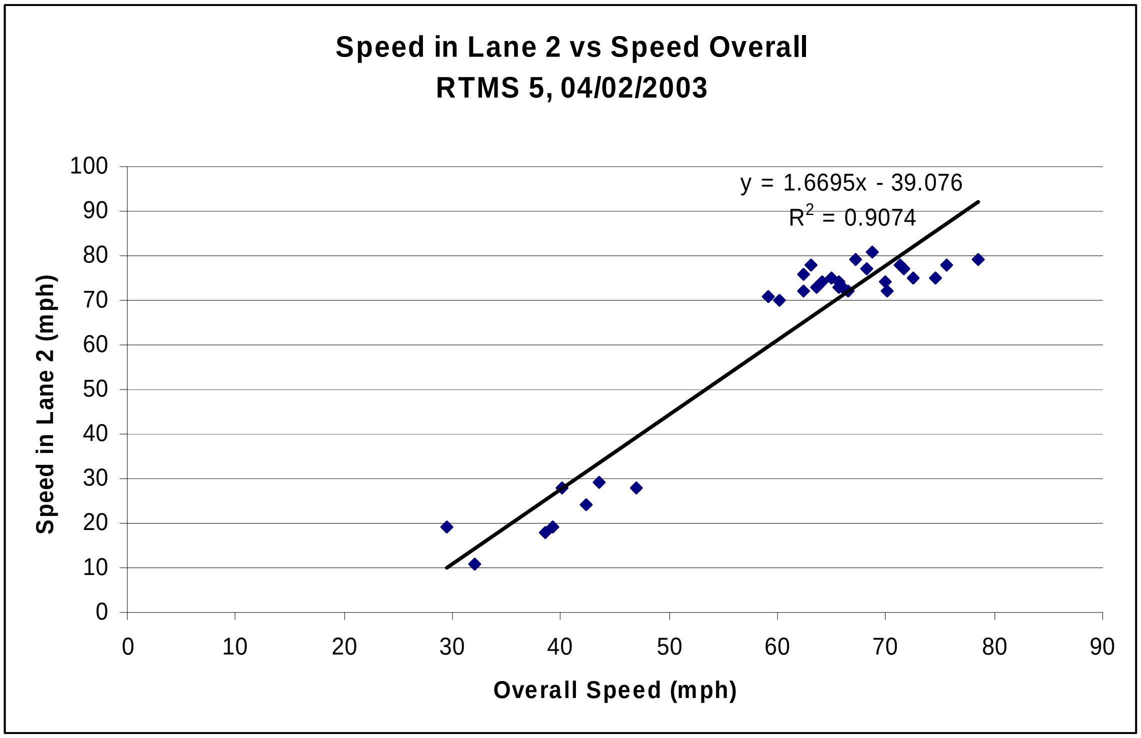


Figure 10. Comparison of Speeds at RTMS 5.

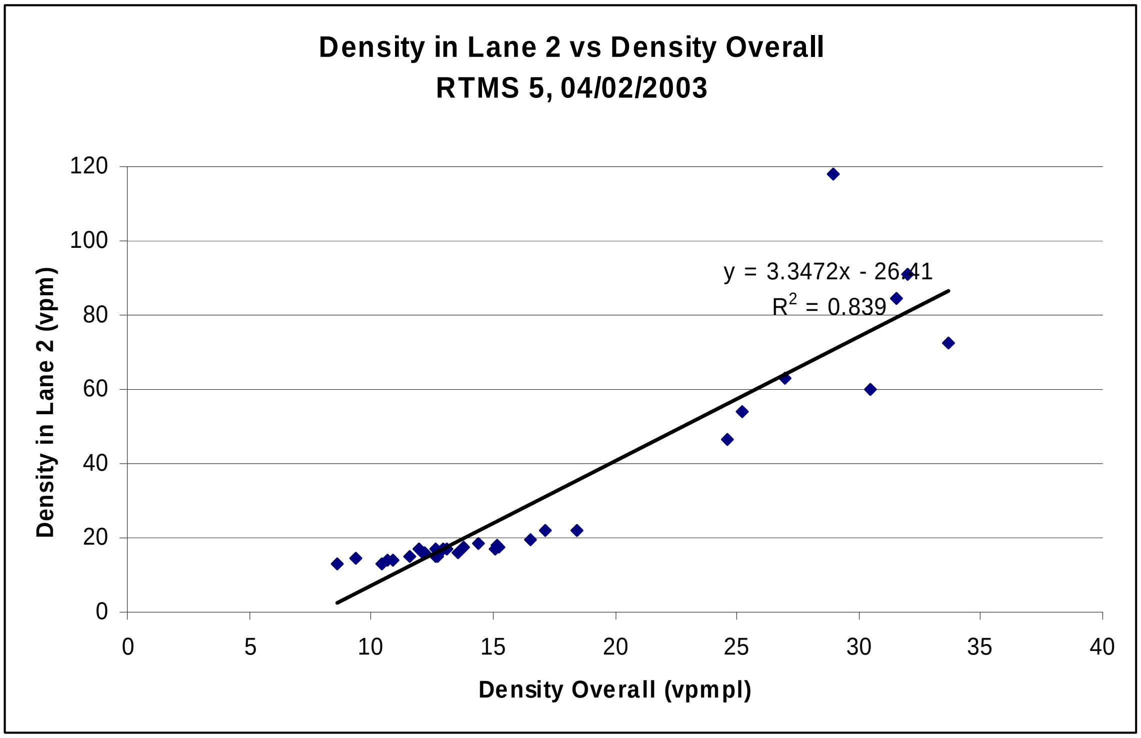


Figure 11. Comparison of Densities at RTMS 5.

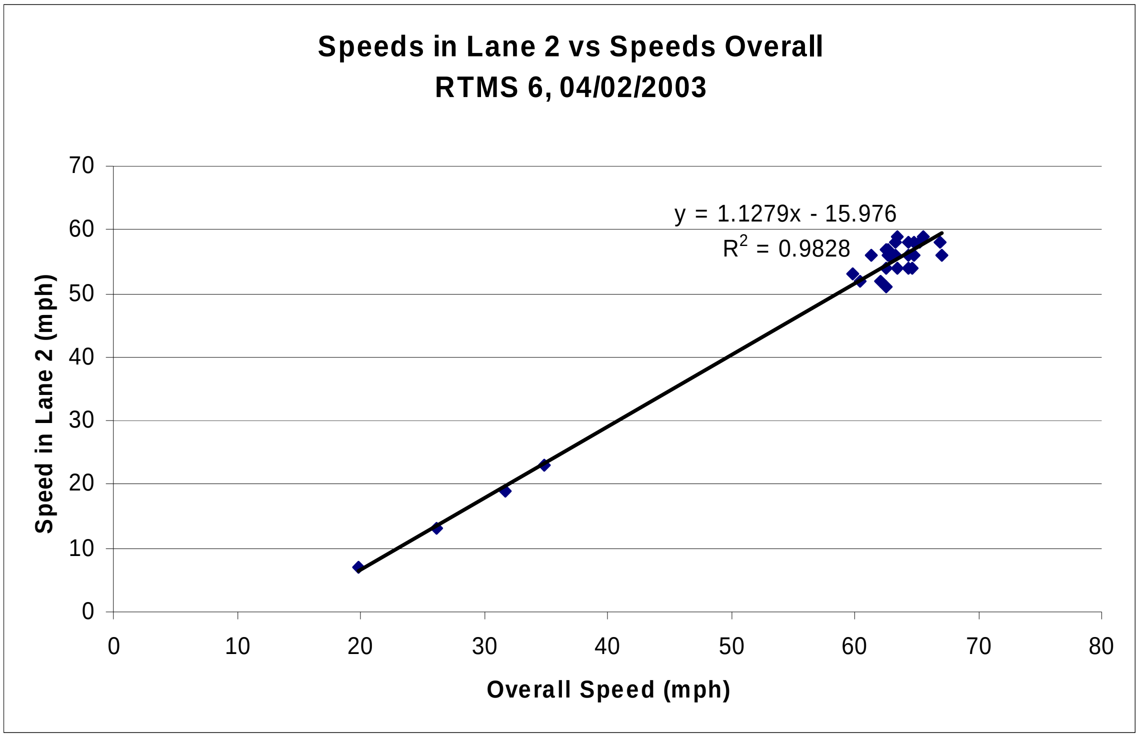


Figure 12. Comparison of Speeds at RTMS 6.

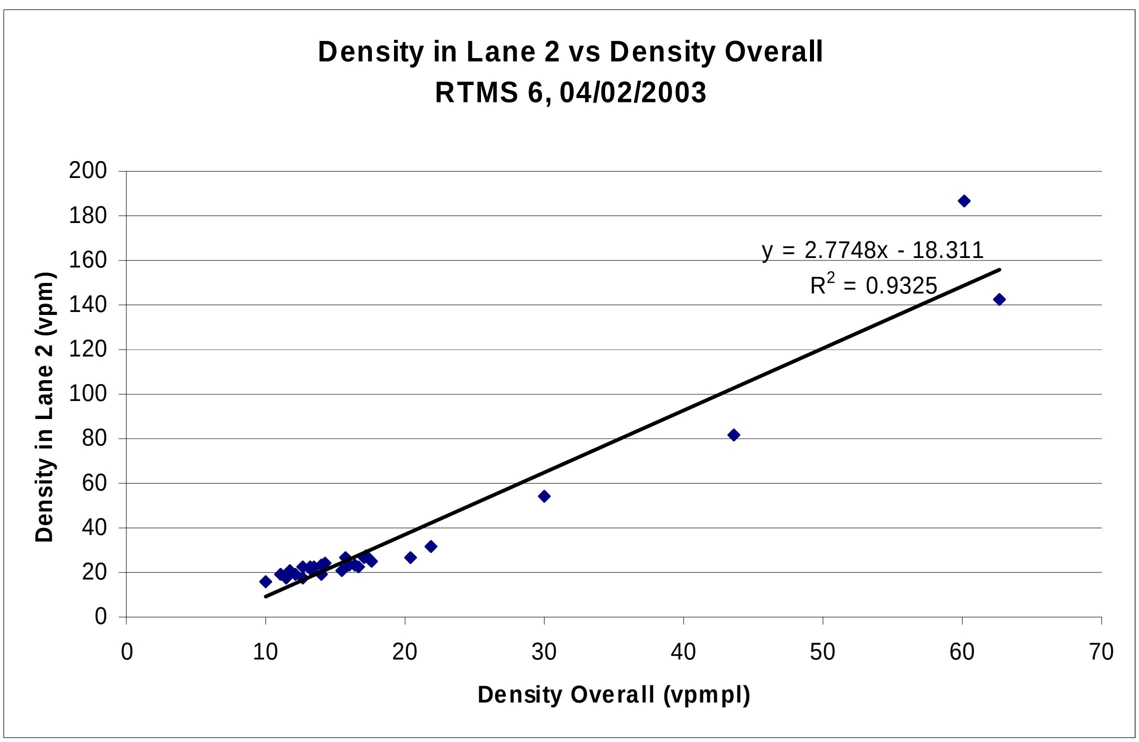


Figure 13.Comparison of Densities at RTMS 6.

Final Transitional Thresholds

The initial thresholds considered for transitions between Late Merge Mode and Incident Mode were drawn from a previous deployment in Springfield, Missouri. After adjusting the speeds to account for the difference between overall average speeds and speeds in Lane 2, the equivalent threshold values were 32 and 37 mph (i.e., 32 mph for the transition from Late Merge to Incident Mode and 37 mph for the transition from Incident to Late Merge Mode). Based on the preliminary data collected at the study site, these thresholds would result in direct transitions from Early Merge to Incident Mode and back. Values of 15 and 20 mph were selected to ensure three distinct traffic scenarios and preclude entering Incident Mode during typical recurring congestion for this site. The threshold speeds for VMS state changes were established from the preliminary data and are shown in Table 9.

Table 9. Mode Transition Speed Thresholds

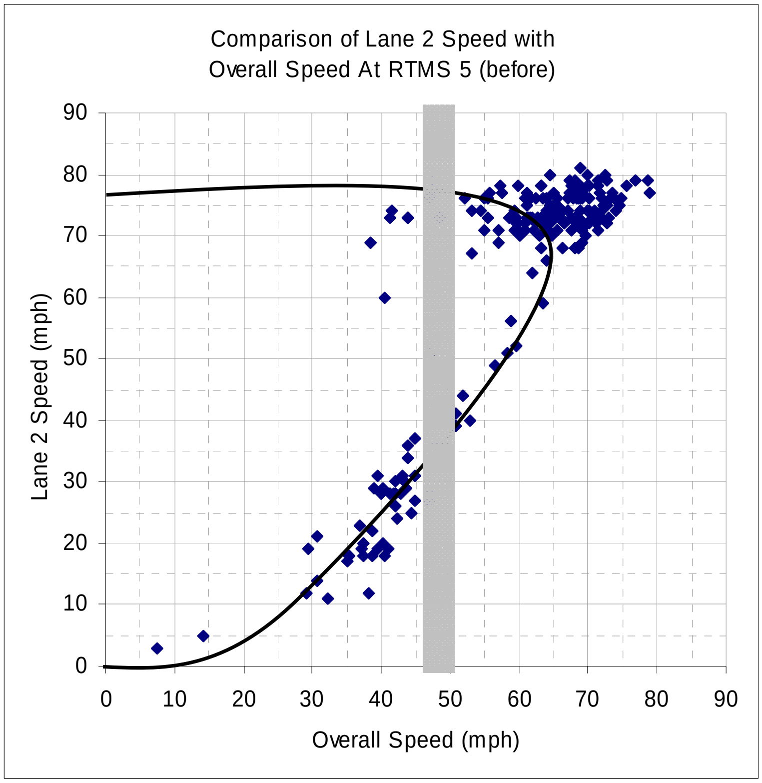
From	To	Lane 2 Avg Speed	Overall Avg Speed	Value Used
Early Merge	Late Merge	35*	46.6	46.6
Late Merge	Early Merge	40	51.3	51.3
Late Merge	Incident	20†	32.4	15.1
Incident	Late Merge	25	37.1	20.1

Post-Study Examination of Thresholds

After all the data collection was complete, the issue of transition thresholds was revisited using the fuller data set, including the after data, which was collected while the system was active. Because the lane-specific data were collected using a sidefire RTMS, very slow moving traffic (less than 10-15 mph) could correspond to exaggerated reporting of densities. Any records containing reported density values of 250 pcpmpl‡ or greater were filtered from the data prior to processing. Additionally, days during which no overall density greater than 25 pcpmpl were also filtered out, simply because such low densities are no of interest for the purposes of this study.

Figure 14 contains plots of the overall average speeds against the average speeds in Lane 2 at RTMS 5 for the period before the system was activated and the period after the system was activated, respectively. The curves on the graphs are identical and are to assist in comparison, only. They are not intended to represent any particular function. The shaded areas indicate the transition region between early merge operation and late merge operation (i.e., if the system is active). Figure 15 shows the analogous plots for data collected at RTMS 6.

* Based on simulations conducted by Pesti.
† Based on deployment in Springfield, Missouri.
‡ 250 pcpmpl corresponds to a vehicle spacing of approximately 21 ft.



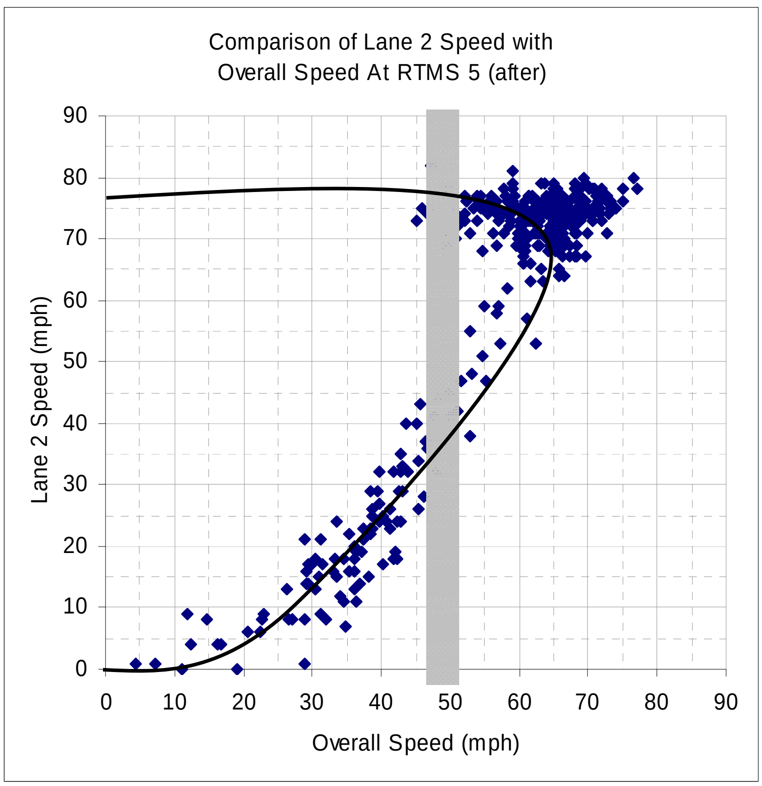
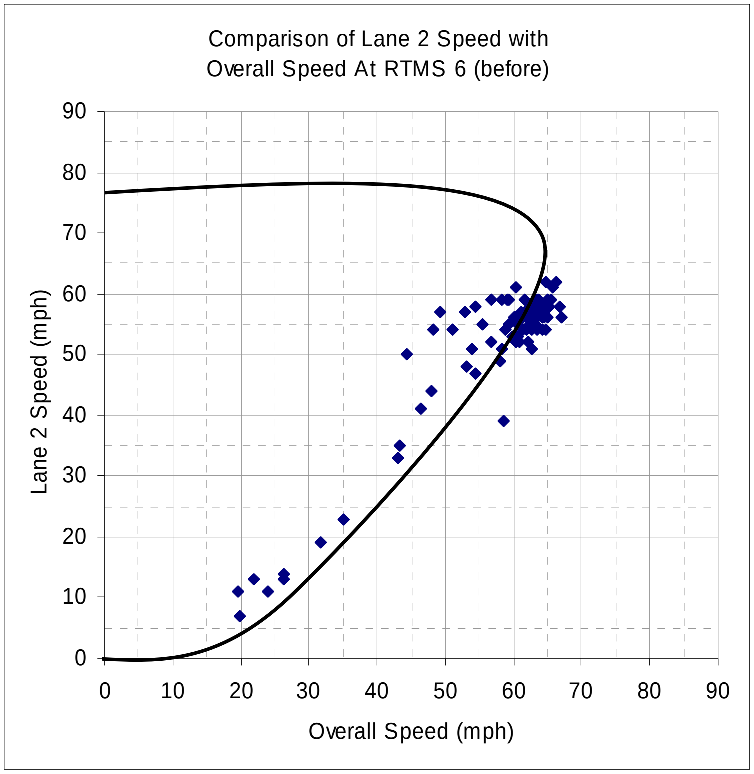


Figure 14. Plot of Overall Speeds vs. Speeds in Lane 2 at RTMS 5.



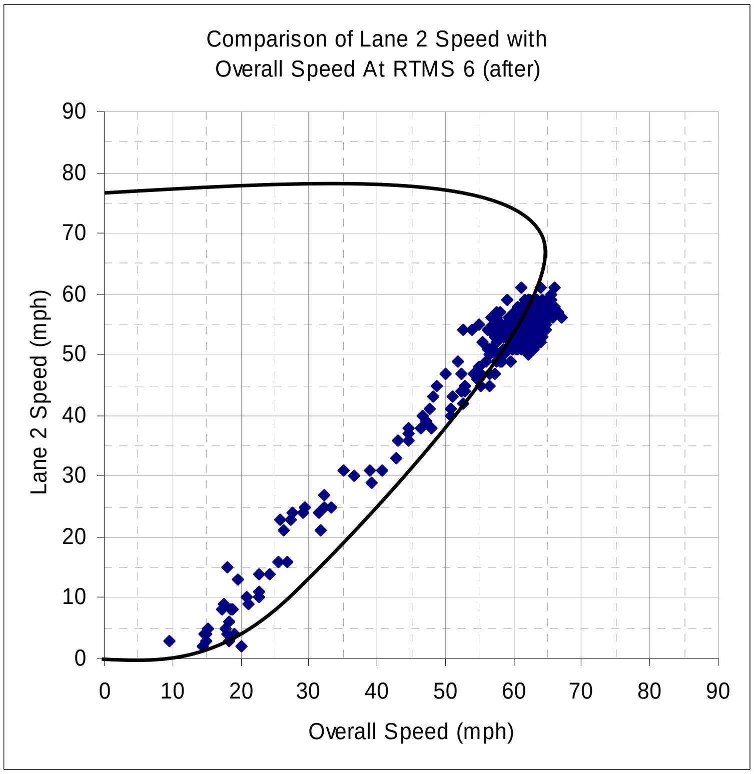
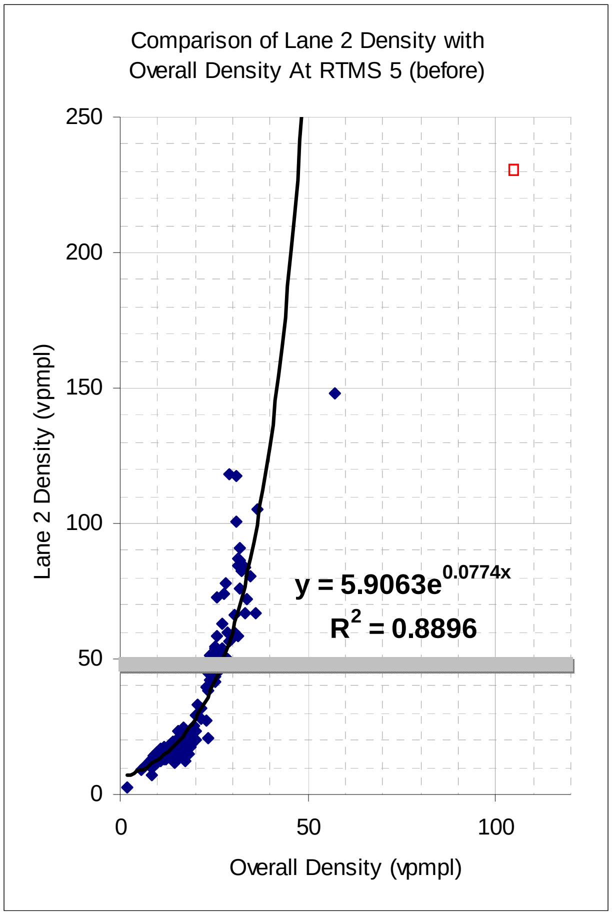


Figure 15. Plot of Overall Speeds vs. Speeds in Lane 2 at RTMS 6.

At both locations, there was no obvious difference between the pattern observed during baseline conditions and that observed with the system active. In the shaded region of each plot at RTMS 5, it can be seen that overall average speeds of between 47 mph and 51 mph can correspond to speeds in Lane 2 of around 35 mph or around 75 mph. For the lower speeds, the chosen threshold speeds seem to be very appropriate surrogates for Lane 2 speeds corresponding to Pesti's thresholds. But this does not hold true for the higher Lane 2 speeds.

When densities overall and in Lane 2 are plotted, as shown in Figure 16, they appear to follow an exponential pattern, providing a cleaner relationship between overall traffic conditions and conditions in Lane 2 than do speeds. In the before data, one point was subjectively categorized as an outlier, and was excluded from the analysis. The point is shown as a (red) hollow square in the plot of before data (coordinates 105,231). While the true function may bend back toward this point at the higher densities, excluding the point provided a better representation of the data in the transition region (45-50 pcpmpl in Lane 2) using an exponential function.



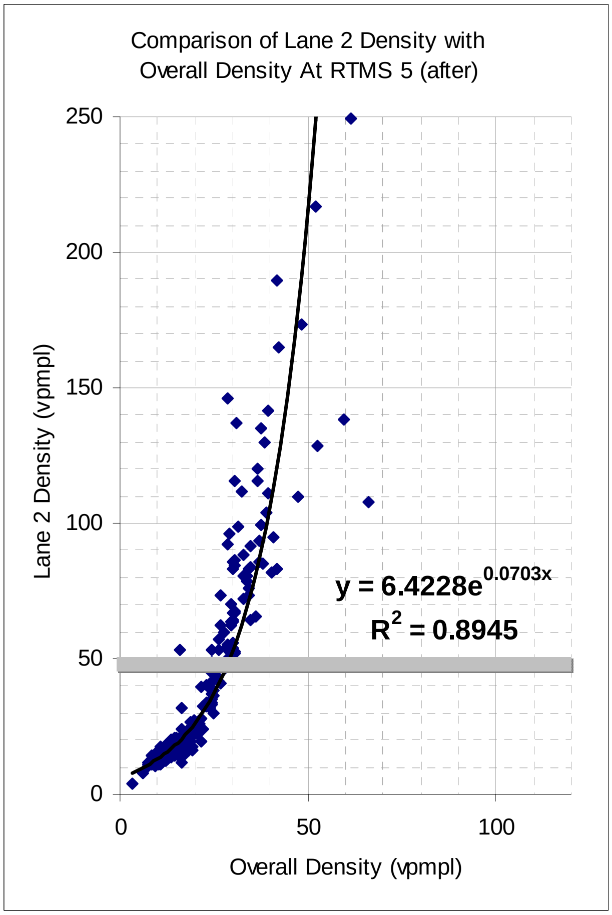


Figure 16. Plots of overall density vs. density in Lane 2 at RTMS 5.

To better illustrate the relationship between the before and the after data, the representative functions are shown together in Figure 17. Given a threshold of 25-30 pcpmpl (overall) for entering late merge operation, the two functions are nearly coincident at lower densities (when both would be operating in early merge mode). When the overall density is higher than the threshold and the system is operating in late merge mode in the after data and early merge mode in the before data, a given overall density corresponds to a higher Lane 2 density in the after data. This is counter to the expectations when drivers are being encouraged to use both lanes all the way to the lane drop. Figure 18 and Figure 19 show analogous data for RTMS 6. The before and after plots at RTMS 6 are very similar.

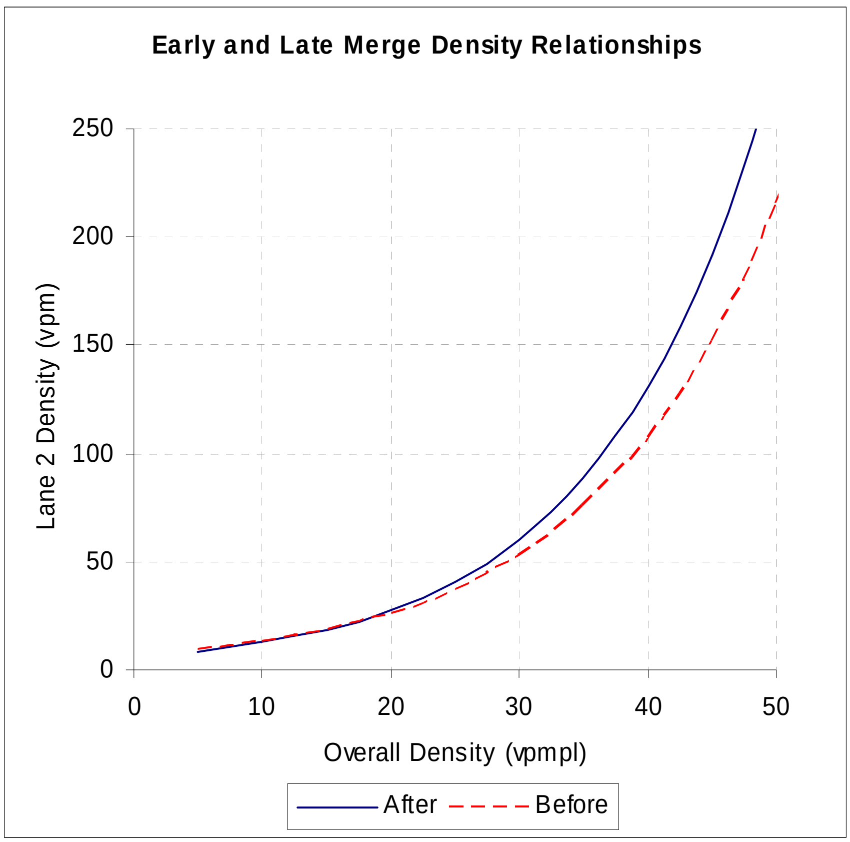
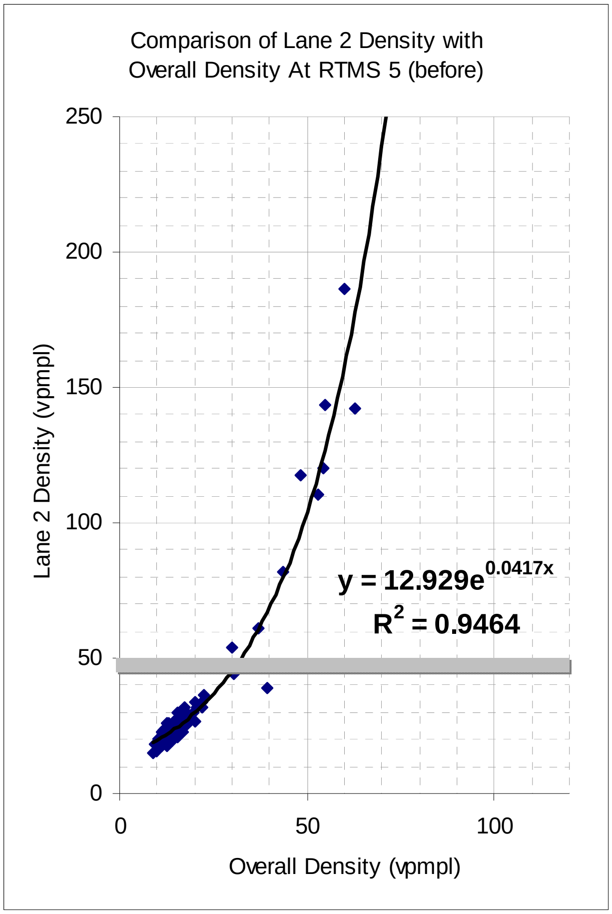


Figure 17. Comparison of Density Relationships at RTMS 5.



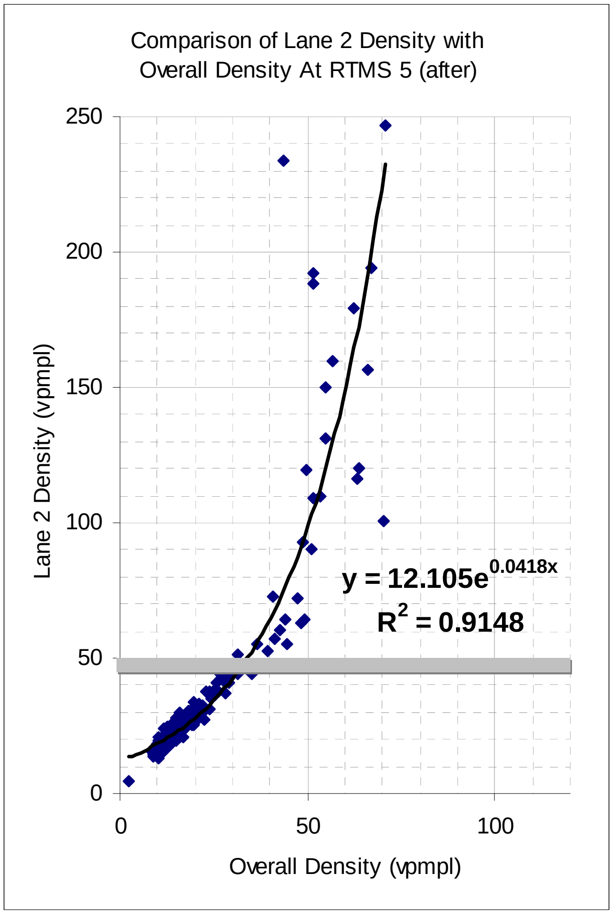


Figure 18. Plots of overall density vs. density in Lane 2 at RTMS 6.

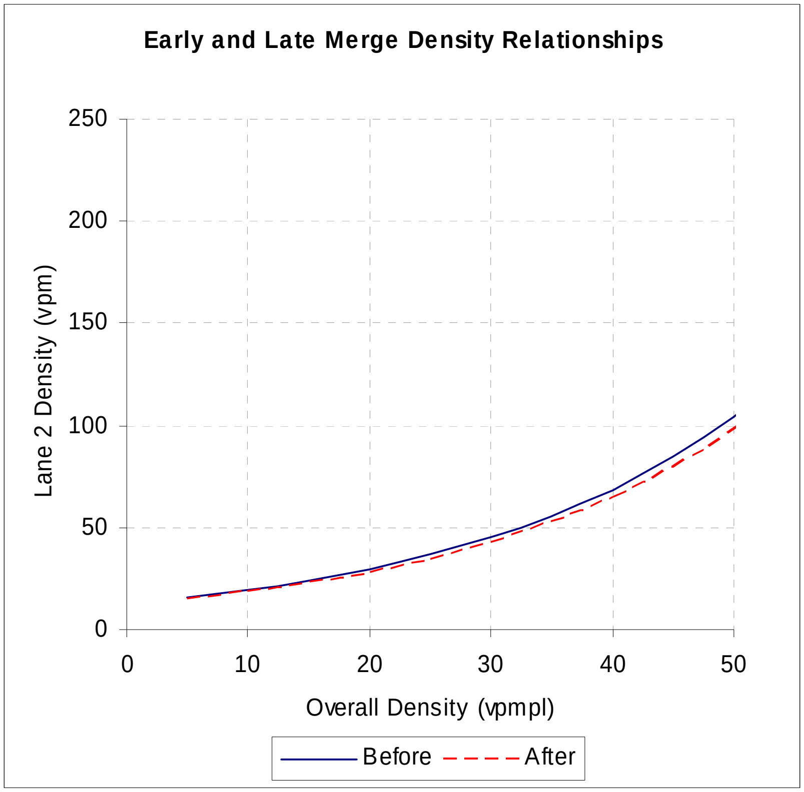


Figure 19. Comparison of Density Relationships at RTMS 6.

System Effectiveness

System effectiveness was examined from two perspectives. First, did the system yield a change in driver behavior? If so, did the change result in an improvement in flow through the work zone? The concept of late merge revolves around the use of the lane being dropped. When operating in late merge mode, the system instructs drivers to use all lanes all the way to the lane drop. We would expect this to result in that lane—Lane 1, the outermost lane, in this case—carrying a higher percentage of the overall volume than when operating in early merge mode. Figure 20 shows a scatter plot of the percent of overall volume using Lane 1 against the overall density. This data was collected at RTMS 5 during the after period, meaning that for densities below about 25, the system would be operating in early merge mode, and for higher densities, the system would be operating in late merge mode. The scatter plots for baseline and treatment conditions at both RTMS 5 and RTMS 6 are provided in Appendix A.

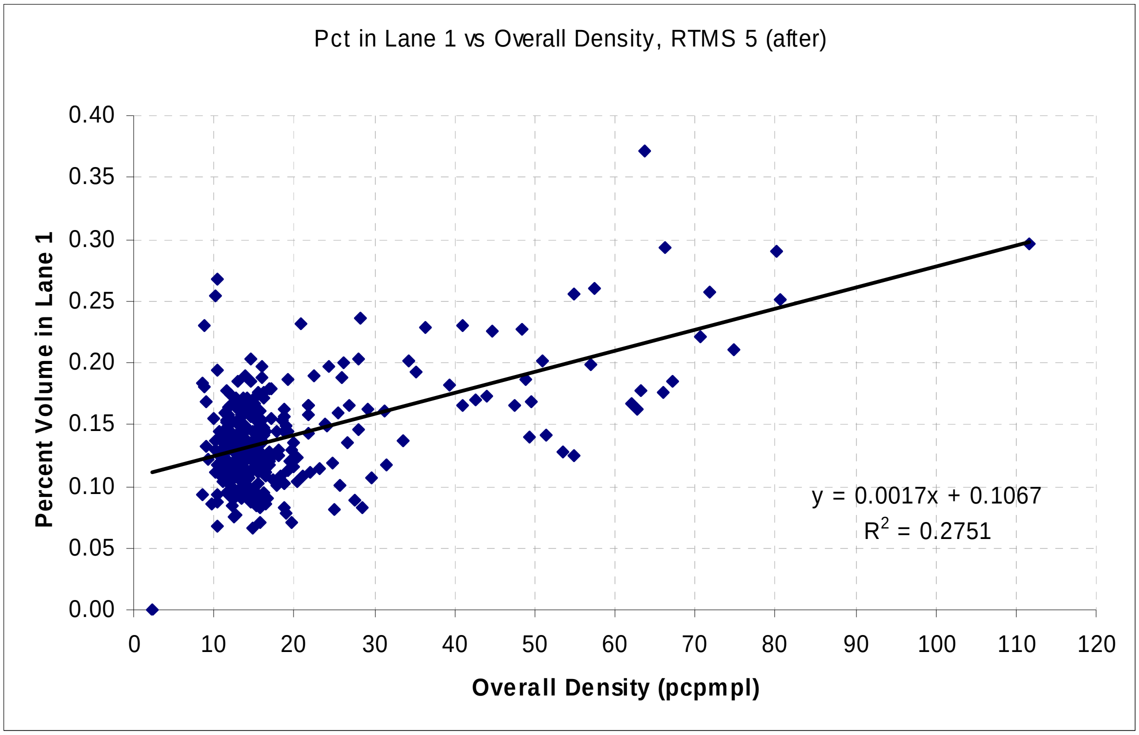


Figure 20. Scatter plot of lane distribution vs. overall density, RTMS 5, after.

Because there is an obvious change in the lane usage as density increases, a simple comparison of averages between before and after data is not appropriate. It was expected that the before and after data would show no difference when densities were in the region indicating early merge operation. It was also expected that at higher densities, where the system would have been operating in early merge mode during the before time period and in late merge mode during the after time period, the percent of vehicles using Lane 1 would be higher in the after data. Figure 21 shows the comparison of the lane usage in the before and after data, categorized by overall density values. The error bars represent the confidence interval ($\alpha = 0.05$) for each subsample. Where the difference between the means of the before and after data was statistically significant at a 95% confidence level, an asterisk was appended to the x-axis label.

Given a threshold for late merge operation in the after time period of about 25 pcpmpl, the lower densities, where the system would have been operating in early merge mode in both time periods, showed no statistically significant differences. At densities greater than 40 pcpmpl, the sample sizes were insufficient to draw a comparison of means. At densities between 20 pcpmpl and 40 pcpmpl, the difference between the early merge operation in the before data and the late merge operation in the after data was statistically significant, with the exception of 35 pcpmpl category, which was very close to being significant, with a p-value of 0.081 (0.05 is needed to indicate statistical significance, in this case). These differences suggest that the system did change driver behavior, resulting in a greater percentage of drivers staying in Lane 1 to the merge (or at least past RTMS 5).

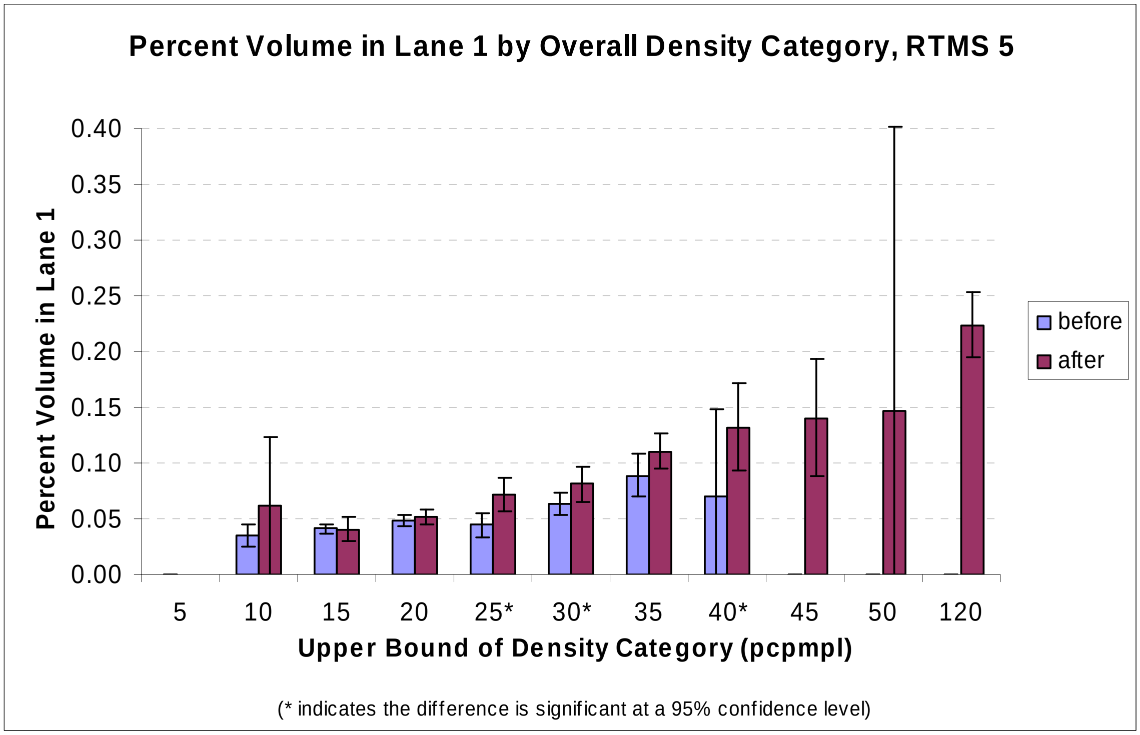


Figure 21. Comparison of lane usage (before and after) by overall density, RTMS 5.

The data collected during late merge operation and baseline data collected while speeds were below the threshold for late merge transition were extracted and compared. Figure 22 shows frequency distributions of all the extracted data (4 minute intervals). For the specific times and days included in this data, see the graph of Late Merge Operation for VMS1 in Appendix B. The baseline data shows no instances where the percent of vehicles in lane 1 exceeded 15%. The distribution for late merge operation shows that 15% usage of Lane 1 was exceeded approximately 20% of the time the system was in late merge mode.

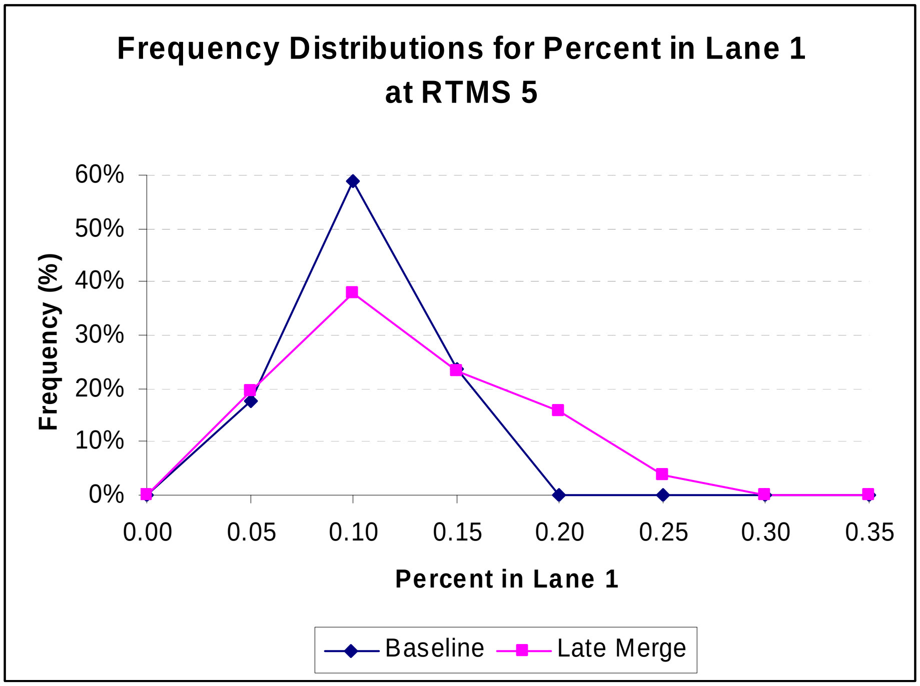


Figure 22. Percent of vehicles in Lane 1 during late merge and analogous baseline conditions.

It does appear that while the system was operating in late merge mode, more drivers were using Lane 1 at RTMS 5. This evidences the system's effectiveness at communicating to the driver. The second indicator of system effectiveness is throughput. That is, did the late merge operation result in improved flow? Two parameters were examined as measures of this aspect of effectiveness, overall volume and average speed of vehicles in Lane 2. Data associated with speeds below the late merge transition threshold were extracted, and compared between three time periods. The first time period was the baseline time period, when the system was monitoring traffic, but was not permitted to enter late merge mode. The second time period was the first week the system was fully functional (i.e., late merge transitions enabled). The third time period was the second and third weeks of operation. The treatment data was divided into these two sets so that the data might be examined to see if drivers either begin to ignore the system after they become accustomed to its presence, or if familiarity with the system results in increased compliance.

Figure 23 shows the frequency distributions for overall volume before and after the system was activated for time periods when the late merge threshold was exceeded. While the before data is somewhat sparse, it appears to have a distribution very similar to that of the after data, suggesting that no practically significant change in capacity occurred between the before data (early merge) and the after data (late merge). Figure 24 shows the frequency distributions for the average speeds in Lane 2. During late merge operation, the distribution is a little less peaked, but shows the same basic pattern.

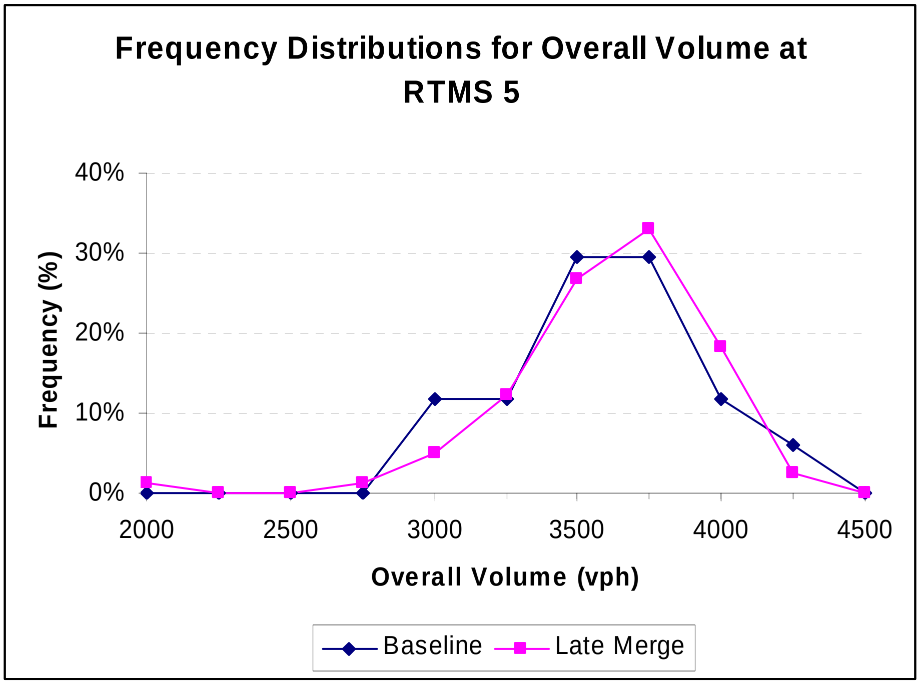


Figure 23. Frequency Distributions for Overall Volume at RTMS 5.

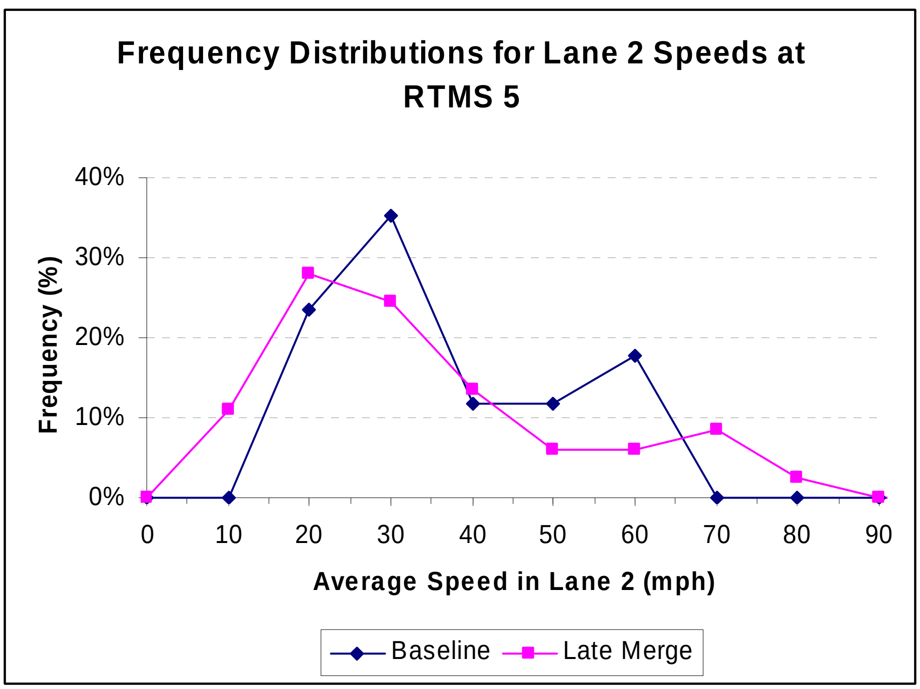


Figure 24. Frequency Distributions for Lane 2 Speeds at RTMS 5.

The Student's t-test was applied to four time period comparisons (baseline vs. all after data, baseline vs. week 1 of the after data, baseline vs. week 2 forward of the after data, and week 1 of the after data vs. week 2 forward of the after data) for three parameters (percent of volume in Lane 1, overall volume, and average speed in Lane 2). Table 10 shows the results of the tests performed on data collected at RTMS 5. The results of tests performed on data from RTMS 6 are given in Appendix C.

Table 10. Results of Student's t-tests at RTMS 5.

	Percent of Total Volume in Lane 1			Volume (vph)			Speed in Lane 2 (mph)		
All baseline vs All treatment		*Before*	*After*		*Before*	*After*		*Before*	*After*
	Mean	**0.077**	**0.100**	**Mean**	**3466**	**3468**	**Mean**	**33.2**	**29.6**
	Variance	0.001	0.003	Variance	107204	111599	Variance	186.6	337.9
	Observations	17	82	Observations	17	82	Observations	17	82
	df	35		df	23		df	29	
	t Stat	-2.322		t Stat	-0.022		t Stat	0.933	
	P(T<=t) two-tail	**0.026**		**P(T<=t) two-tail**	**0.983**		**P(T<=t) two-tail**	**0.358**	
	t Critical two-tail	2.030		t Critical two-tail	2.069		t Critical two-tail	2.045	
All baseline vs Week 1 treatment		*Before*	*Week 1*		*Before*	*Week 1*		*Before*	*Week 1*
	Mean	**0.077**	**0.063**	**Mean**	**3466**	**3329**	**Mean**	**33.2**	**36.2**
	Variance	0.001	0.001	Variance	107204	167768	Variance	186.6	375.3
	Observations	17	24	Observations	17	24	Observations	17	24
	df	37		df	38		df	39	
	t Stat	1.248		t Stat	1.192		t Stat	-0.576	
	P(T<=t) two-tail	**0.220**		**P(T<=t) two-tail**	**0.241**		**P(T<=t) two-tail**	**0.568**	
	t Critical two-tail	2.026		t Critical two-tail	2.024		t Critical two-tail	2.023	
Week 1 treatment vs Week 2 and forward		*Week 1*	*Week 2*		*Week 1*	*Week 2*		*Week 1*	*Week 2*
	Mean	**0.063**	**0.115**	**Mean**	**3329**	**3526**	**Mean**	**36.2**	**26.9**
	Variance	0.001	0.003	Variance	167768	79329	Variance	375.3	302.8
	Observations	24	58	Observations	24	58	Observations	24	58
	df	60		df	32		df	39	
	t Stat	-5.164		t Stat	-2.155		t Stat	2.043	
	P(T<=t) two-tail	**0.000**		**P(T<=t) two-tail**	**0.039**		**P(T<=t) two-tail**	**0.048**	
	t Critical two-tail	2.000		t Critical two-tail	2.037		t Critical two-tail	2.023	
All baseline vs Week 2 treatment and forward		*Before*	*Week 2*		*Before*	*Week 2*		*Before*	*Week 2*
	Mean	**0.077**	**0.115**	**Mean**	**3466**	**3526**	**Mean**	**33.2**	**26.9**
	Variance	0.001	0.003	Variance	107204	79329	Variance	186.6	302.8
	Observations	17	58	Observations	17	58	Observations	17	58
	df	41		df	23		df	33	
	t Stat	-3.648		t Stat	-0.680		t Stat	1.579	
	P(T<=t) two-tail	**0.001**		**P(T<=t) two-tail**	**0.503**		**P(T<=t) two-tail**	**0.124**	
	t Critical two-tail	2.020		t Critical two-tail	2.069		t Critical two-tail	2.035	

The results of the t-tests support the initial observations from the graphs and frequency distributions. Statistically significant differences (95% confidence level) were observed between the before and after data with respect to the percent of volume in Lane 1. Differences with respect to overall volume and speed in lane 2 were not statistically significant. This held true for RTMS 6, as well, although the differences in percent volume in Lane 1 were much smaller.

Average volumes during congested conditions (i.e., when thresholds for late merge operation were exceeded) were higher at RTMS5 with the system active than during the before period.

Volumes actually decreased slightly during the first week of late merge operation (3466 vph to 3329 vph), although the difference was not statistically significant. Between week 1 and week 2 of late merge operation, the volumes increased approximately 200 vph, from 3329 vph to 3526 vph. This difference was statistically significant. The difference between the before data and the data collected after the first week of late merge operation (60 vph) was not significant.

Another expected benefit of a late merge system is reduced queue lengths due to fuller utilization of queue storage capacity. For this analysis, queue was defined as "traffic conditions meeting the criteria for late merge operation." Given this definition, queue times were compared between VMS 1 and VMS 2. Figure 25 shows a plot of queue durations at VMS 1 and VMS 2. Baseline includes all data collected prior to April 14, when the system was activated (i.e., includes the week of testing). The first week following system activation was separated from the remainder of the after data. It was desirable to filter out incident-related congestion, whose queue duration is governed by the duration of the incident rather than by the performance of the merge operation. Toward that end, daily queue durations were extracted for the morning peak period only. If for a given day a queue existed at 8:00 AM, that duration was used as that day's value. If no queue existed at that time, that day was excluded.

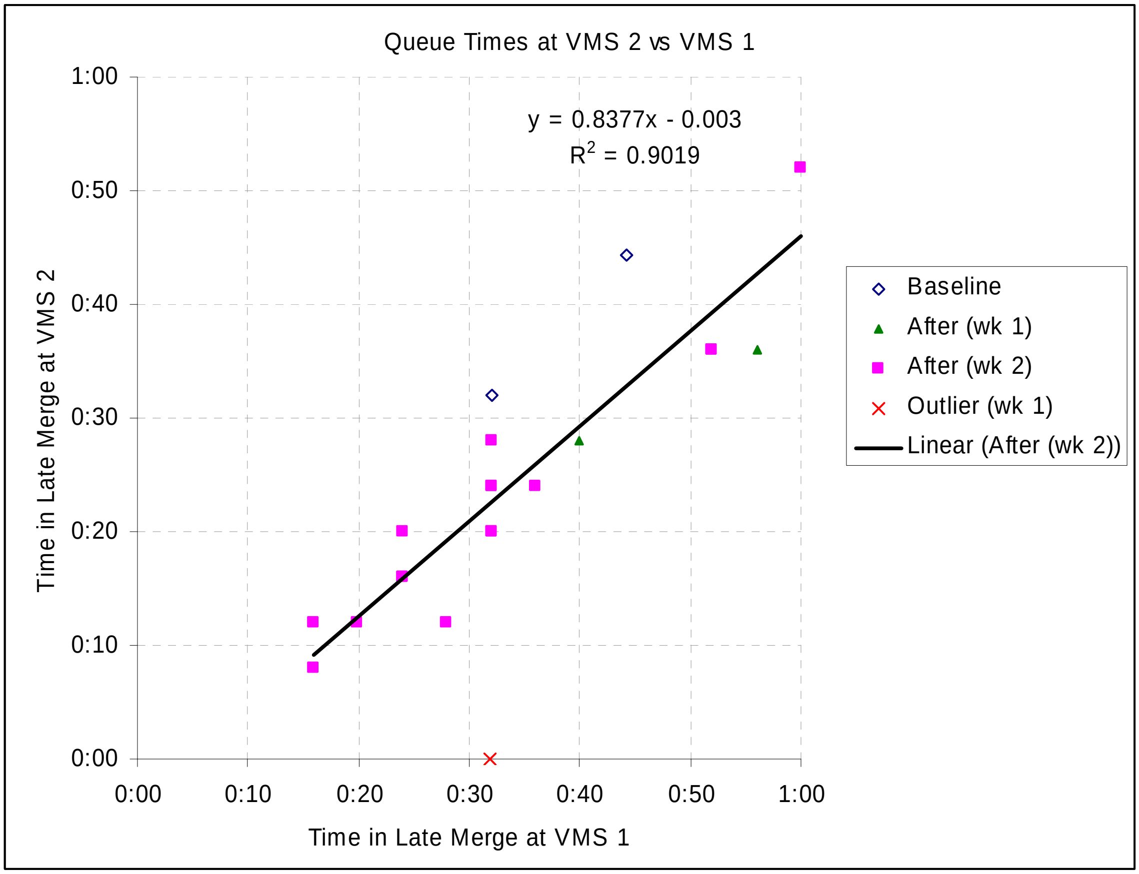


Figure 25. Comparison of Queue Times at VMS 1 and VMS 2

If the system results in better utilization of the queue capacity of the segment, then for the same queue duration at VMS 1, a lesser duration will be observed at VMS 2. Only two samples were available from the before data. Other days had either no queuing during the morning peak or such extensive queuing through the day that some other factor is probably affecting the queue duration. Given the sparse data, it is not surprising that the differences between the averages before and after deployment were not statistically significant. However, the plot of the values in Figure 25 shows a pattern that is consistent with reduced queue durations after the system was activated. The trend line shown in the graph is based on the after data, week 2 and following. If the system was effective at reducing queue lengths, then the queue durations at any upstream point would be expected to be shorter. The before data points lie above the trend line for the after data, meaning that for the same duration at VMS 1, the before data shows longer durations at VMS 2. If, as other data has suggested, drivers required a week to become accustomed to the system, the data from the first week following system activation would also lie above the trend line. But that does not occur in this data. It is important to reemphasize that these results were not statistically significant, meaning that they can only be taken as a suggestion of patterns that may actually exist, but which need to be repeated in other data before they can be used to draw any conclusions. The patterns do suggest that system activation reduced queue lengths.

CONCLUSIONS

Overall, the evaluation supports the potential of dynamic late merge systems to improve the operation of highway lane drops, and highlights the importance of placing sensors with careful consideration of highway elements, particularly entrance and exit ramps.

Driver Compliance

Driver compliance was examined in terms of the percent of the total volume still in Lane 1 at RTMS5. Values decreased slightly during the first week of deployment, but the difference was not statistically significant. From the second week of deployment on, the percentage of drivers in Lane 1 at RTMS5 was greater than the before data, increasing to 11.5% from about 6% before the system was activated. The percentage during the first week after activation was slightly less than 6%. These numbers suggest both that drivers did change their behavior, and that the behavior change required some "training" period to be fully realized. Observations of the merging area revealed that the entrance ramp from 57^{th} St had a significant effect on lane distributions, prompting drivers to merge early in deference to the entering traffic. This ran counter to the desired behavior during late merge operation.

Flow Impacts

There did not appear to be an effect of the system on flow. Average volumes during late merge conditions (i.e., when thresholds for late merge operation were exceeded) decreased by 200 vph during the first week following system activation compared to before activation, then increased during subsequent weeks to slightly above the baseline values. If the decrease can be attributed to drivers becoming accustomed to the late merge concept, then these observations would support the notion that drivers require about a week to accept the late merge concept. The net change in volumes, however, did not show a significant improvement over baseline values. Because of the sparseness of data, particularly congested data during the before time period, the analysis should not be taken to mean late merge in general does or does not improve flow, but rather that this study was inconclusive on the issue.

System Operation

The overlapping speed ranges did appear to prevent oscillating back and forth between modes. There were some instances where oscillation seemed to be occurring (see May 2 data for VMS 2 in Appendix D), but such instances were rare, and this particular instance is an oscillation between late merge mode and incident mode, which both operate under a late merge paradigm. (Incident mode triggers warning messages at the upstream VMS which do not occur during late merge mode.)

Additional research will be necessary to determine whether or not the particular thresholds used provided the most efficient operation.

System Deployment

The communications link is likely to be a governing factor in determining where systems of this type are and where they are not a viable solution. The particular medium employed required line of sight from transmitting to receiving antenna. While there were several vertical curves that restricted the placement of the field devices, satisfactory locations were identified. Some flexibility can be added in the form of field relay stations, but terrain must still be considered carefully before a site is committed for system deployment. No relay stations were used in this deployment.

The communications also required that the Central System Controller (CSC) be located on or near the site. A suitable location was available, although the CSC communications antenna needed to be elevated to achieve line of sight with the nearest field components in each direction. A telephone pole was erected, and the antenna was mounted atop the pole at a height of approximately 45 ft.

All field units were powered by a battery array supplemented by a solar panel. No maintenance was performed on the batteries during the deployment, and the power supply in the RTMS units failed after 5 weeks. Presumably, a nominal amount of maintenance (e.g., adding water every 2-3 weeks) would have prevented these failures.

The remote connection to the CSC was inoperable during most of the evaluation. The root cause of the problem was not determined. The system provider reported that such problems are extremely rare. This is also an unusual case because there were no on-site personnel assigned to the evaluation, making even simple diagnostic tasks difficult, requiring an hour's drive from the University to the work site.

The presence of an entrance ramp immediately prior to the lane drop appeared to have a significant negative impact on the system's effectiveness with respect to improving flow through the merge during periods of high congestion. Other system benefits (e.g., reducing the queue length and warning drivers of downstream congestion) were likely unaffected. Such sites should still be considered candidates for this type of system. But, where multiple sites are vying for system deployment, this issue should be included in the considerations.

The placement of VMS3 at an interchange resulted in the speeds of exiting vehicles being included in the reported data. Consequently, average speeds during any given time period were heavily influenced by exiting volume. Since exiting volumes at this interchange could not be determined with the system configuration used, the data collected at VMS3 could not be effectively used in statistical analyses.

Evaluation

The site was stable (i.e., no geometric changes) near the merge for the duration of the evaluation. It was learned after the evaluation that temporary construction upstream of the evaluation site resulted in a lane closure. The schedule of these closures is unavailable, and thus their impact on the data cannot be determined. The entrance ramp immediately prior to the merge appeared to have a significant effect on driver lane choice. This effect probably diluted the effects of the system, reducing the degree to which the system's potential effectiveness is evident in the data collected.

The congestion occurring on the site proved to be much less than was expected, possibly due to greater diversion than anticipated. The sparseness of data may have hidden some of the effects of the system from being identified statistically.

VMS3 was located adjacent to a segment which included a deceleration lane for a loop exit ramp. It was originally thought that the sensor could be positioned to exclude exiting traffic from the data, but in the post analysis, it was evident that the speeds reported by that sensor did include the exiting traffic, which was considerably slower than the through traffic, on the whole.

RTMS5 was positioned about half way between VMS1 and VMS2 in order to obtain a more complete profile of traffic characteristics along the study segment. In retrospect, it may have been more valuable to have co-located RTMS5 with VMS1. This would have provided lane distributions nearer to the lane drop and would have allowed a direct validation of both data sets via cross comparison.

RECOMMENDATIONS

It is recommended that density be used in lieu of speed as the threshold parameter.

The relationship between overall density and density in Lane 2 should not be applied to other sites without either additional research that confirms the relationship presented in this work, or site specific calibration of the relationship. Sites where the nearest entrance ramp to the lane drop is farther upstream are likely to experience significantly different lane distributions compared to this site.

Including an incident mode in the operational scheme is a promising concept, and further study is merited to see if driver behavior suggests there is potentially an associated safety benefit. However, for incident mode, using a simple threshold speed (or density) as done in this study cannot be recommended across the board. In more congested corridors, flow breakdown may occur regularly. In such cases, more sophisticated algorithms are merited. Triggers may need to consider one or more of the following.

- Upstream-downstream speed differentials
- Sudden reductions in speed
- Speed reductions when volumes are relatively low

Every deployment needs to have someone assigned to oversee the system operation who can perform a visual check on at least a daily basis and perform maintenance weekly or as needed.

Remote validation of the data is an important aspect of system operation. During this evaluation, one sensor malfunctioned and began repeating the same data report for every time period. Because data was being reported, and because the remote data download was not working properly, the malfunction was not discovered for several days (a single pass through the sight would not reveal this malfunction; it required multiple passes, noting that one of the VMS displayed an identical downstream speed during each pass). Alternatively, a simple check (looking daily at a graph of the reported speeds) would be sufficient to identify this type of error. It would be even better if the CSC software would run such routine checks and issue warnings when some aspect of the data appears to be suspicious.

Including entering and exiting traffic in the data could adversely affect system operation. Slower entering or exiting vehicles could cause the system to report late merge conditions when the opposite was actually true. Sensors should be placed and aimed carefully to preclude entering and exiting traffic from being recorded, unless the sensor is able to provide lane distributions so that the entering or exiting traffic can be filtered from the through traffic.

It is recommended that all VMS be placed on the outside shoulder when the lane being dropped is the outer lane. The effects of locating VMS 0 on the inside shoulder were not evaluated in this study, subjective assessment suggested that its effects were nominal at best.

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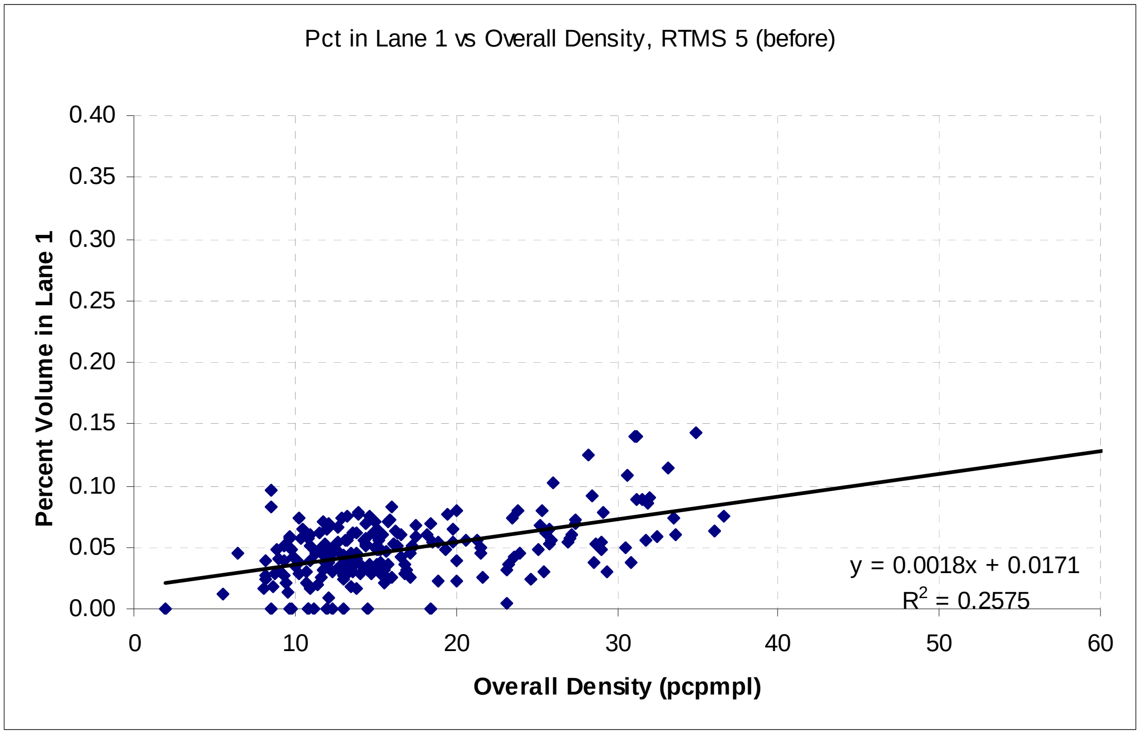
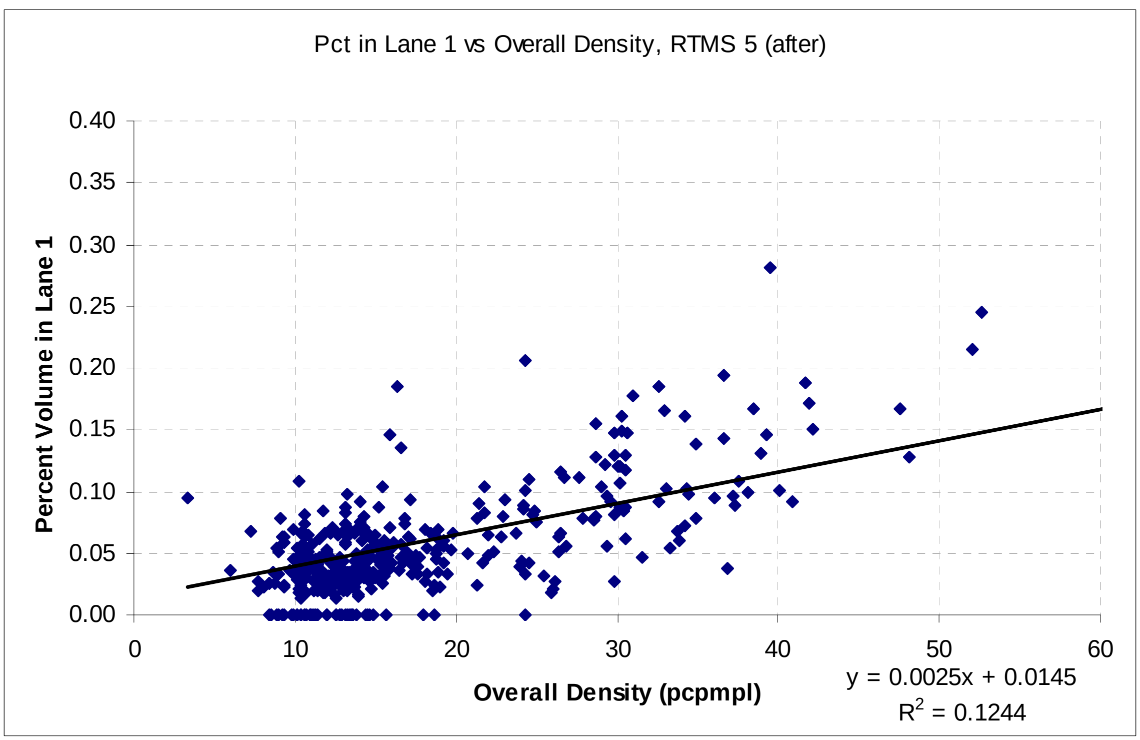
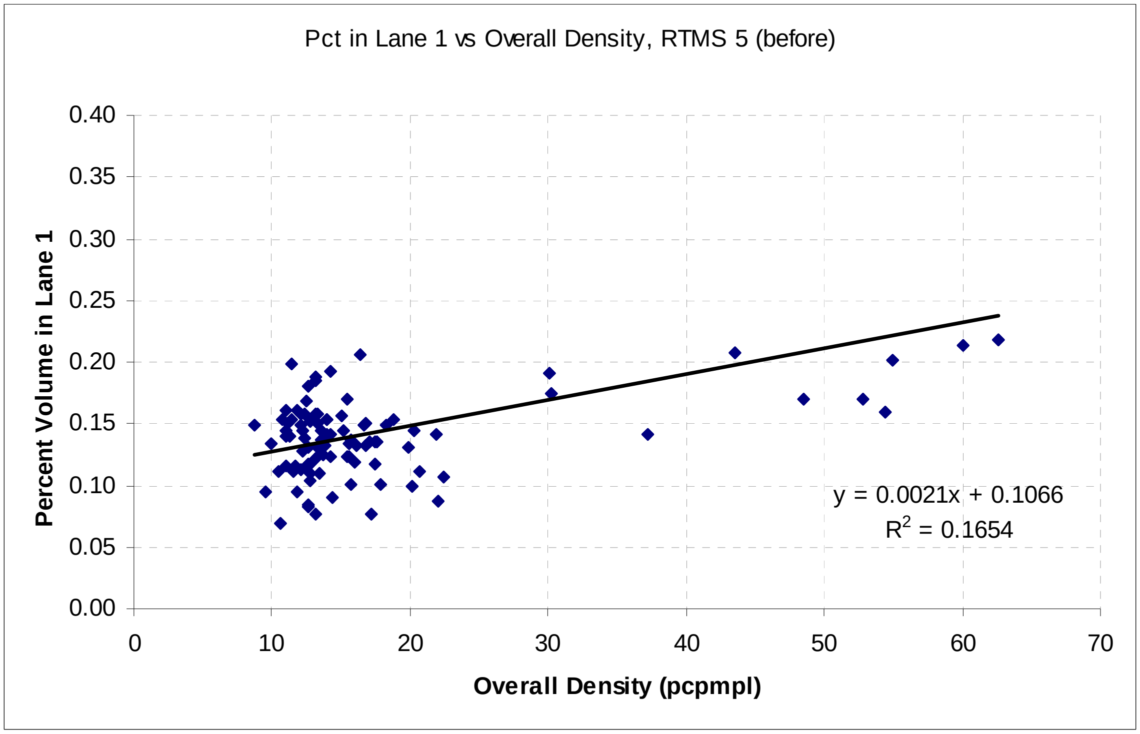
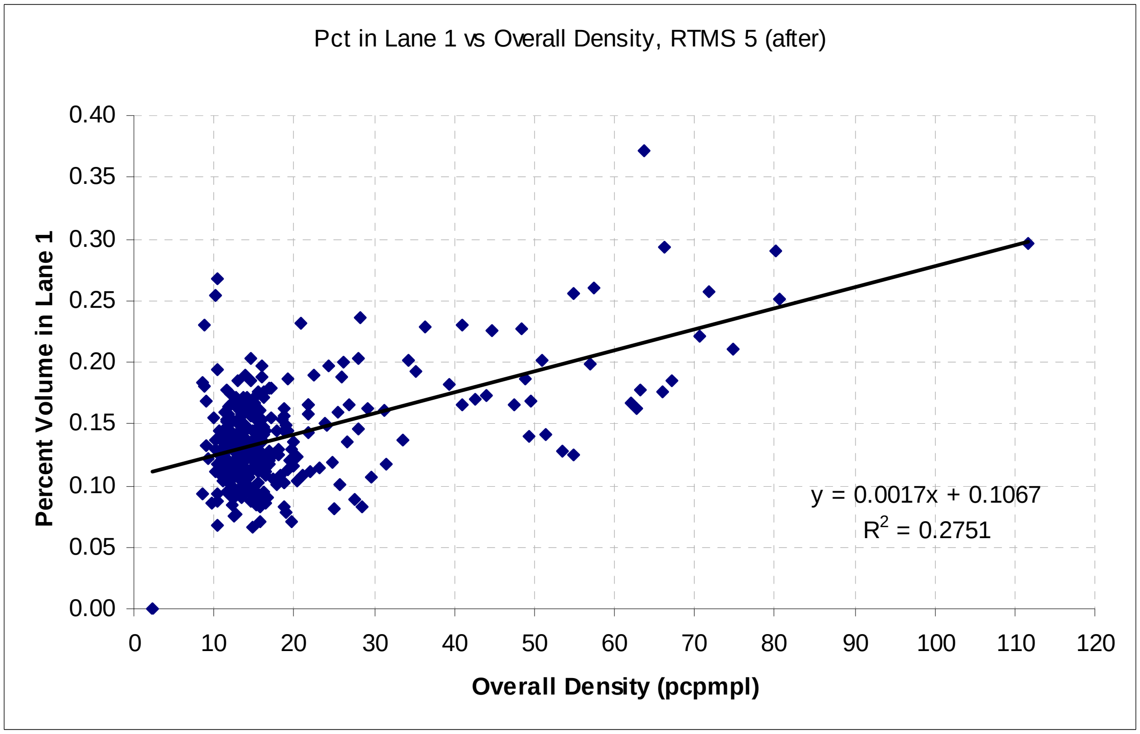
APPENDIX A

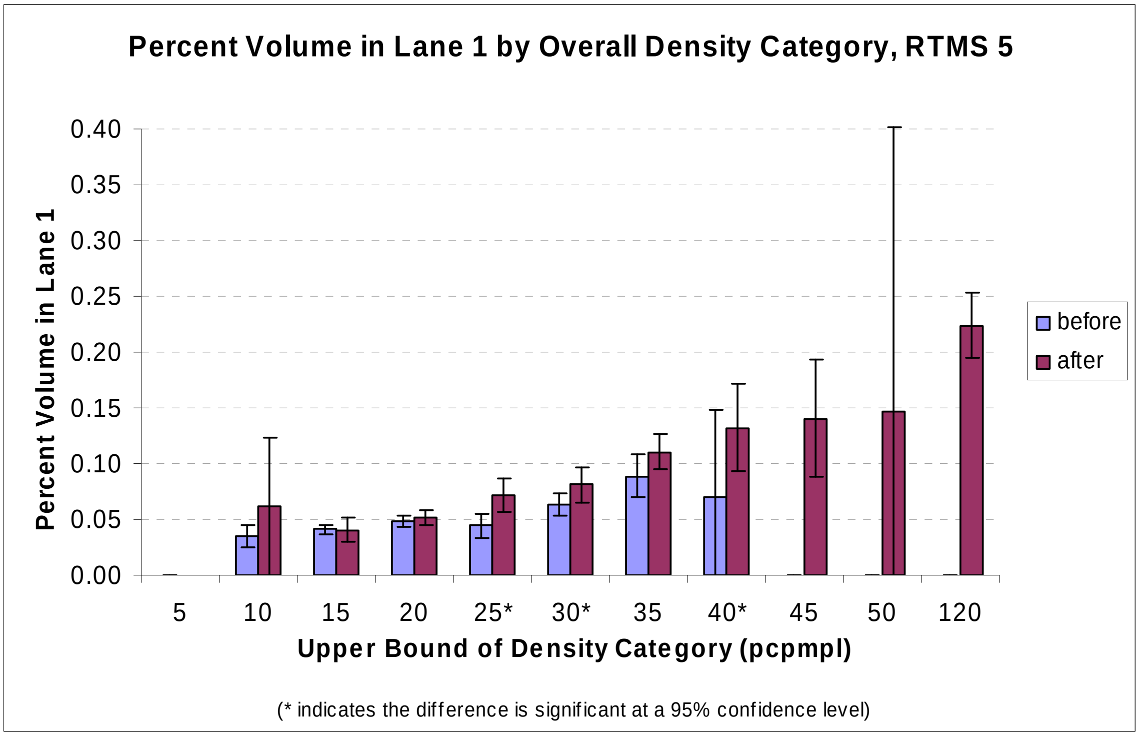
Percent Volume in Lane 1 vs Overall Density

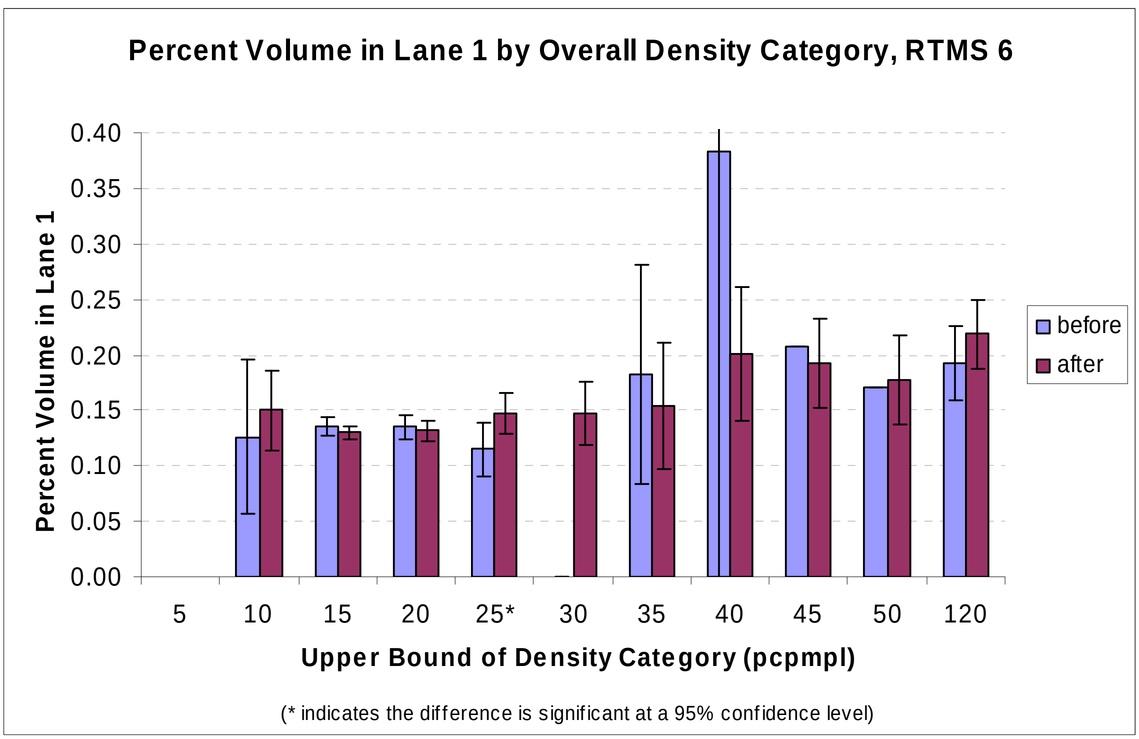





Pct in Lane 1 vs Overall Density, RTMS 5 (before)
Percent Volume in Lane 1
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
10
20
30
40
50
60
70
Overall Density (pcpmpl)
y = 0.0021x + 0.1066
R2 = 0.1654

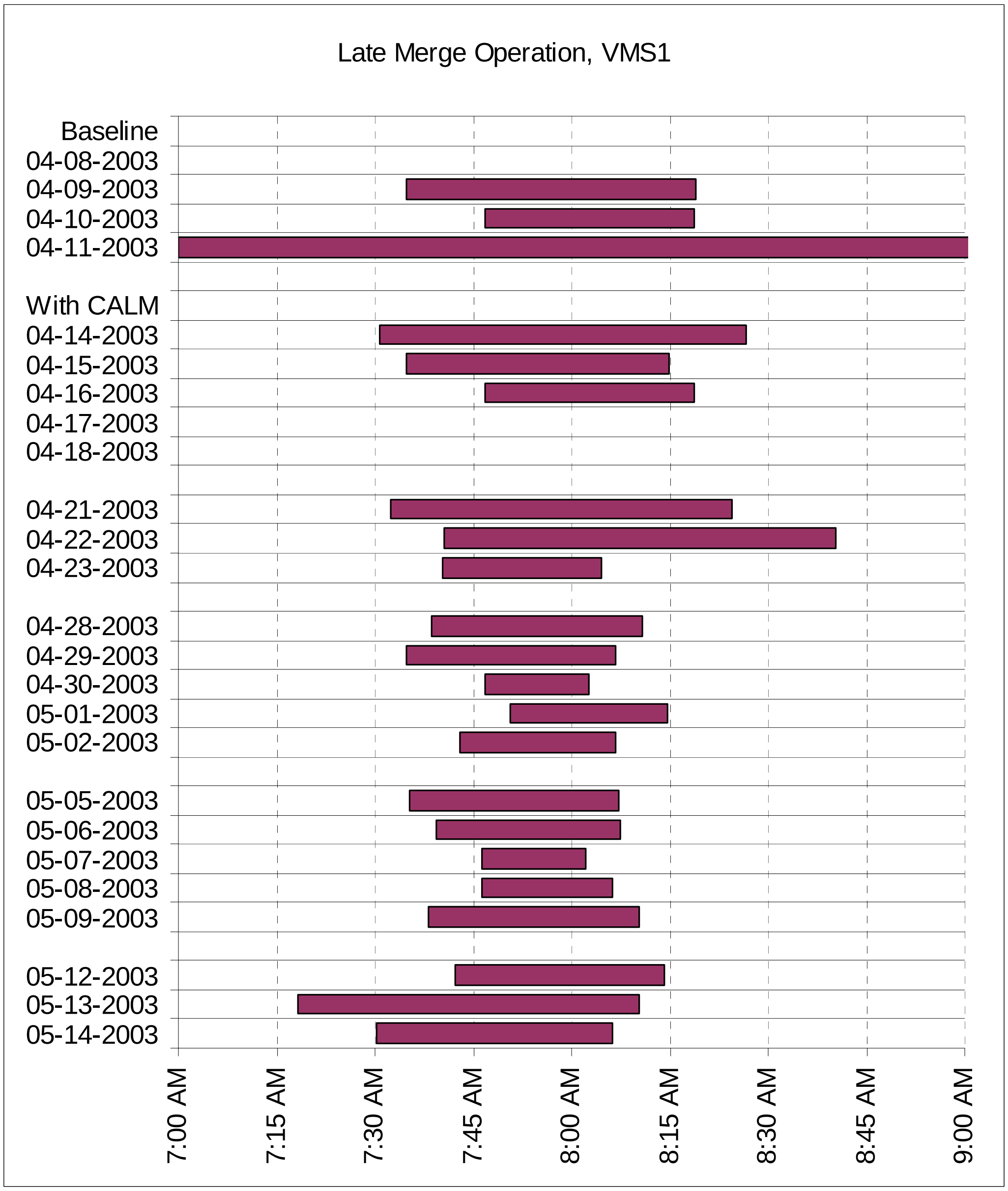

Pct in Lane 1 vs Overall Density, RTMS 5 (after)
Percent Volume in Lane 1
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
10
20
30
40
50
60
70
80
90
100
110
120
Overall Density (pcpmpl)
y = 0.0017x + 0.1067
R2 = 0.2751

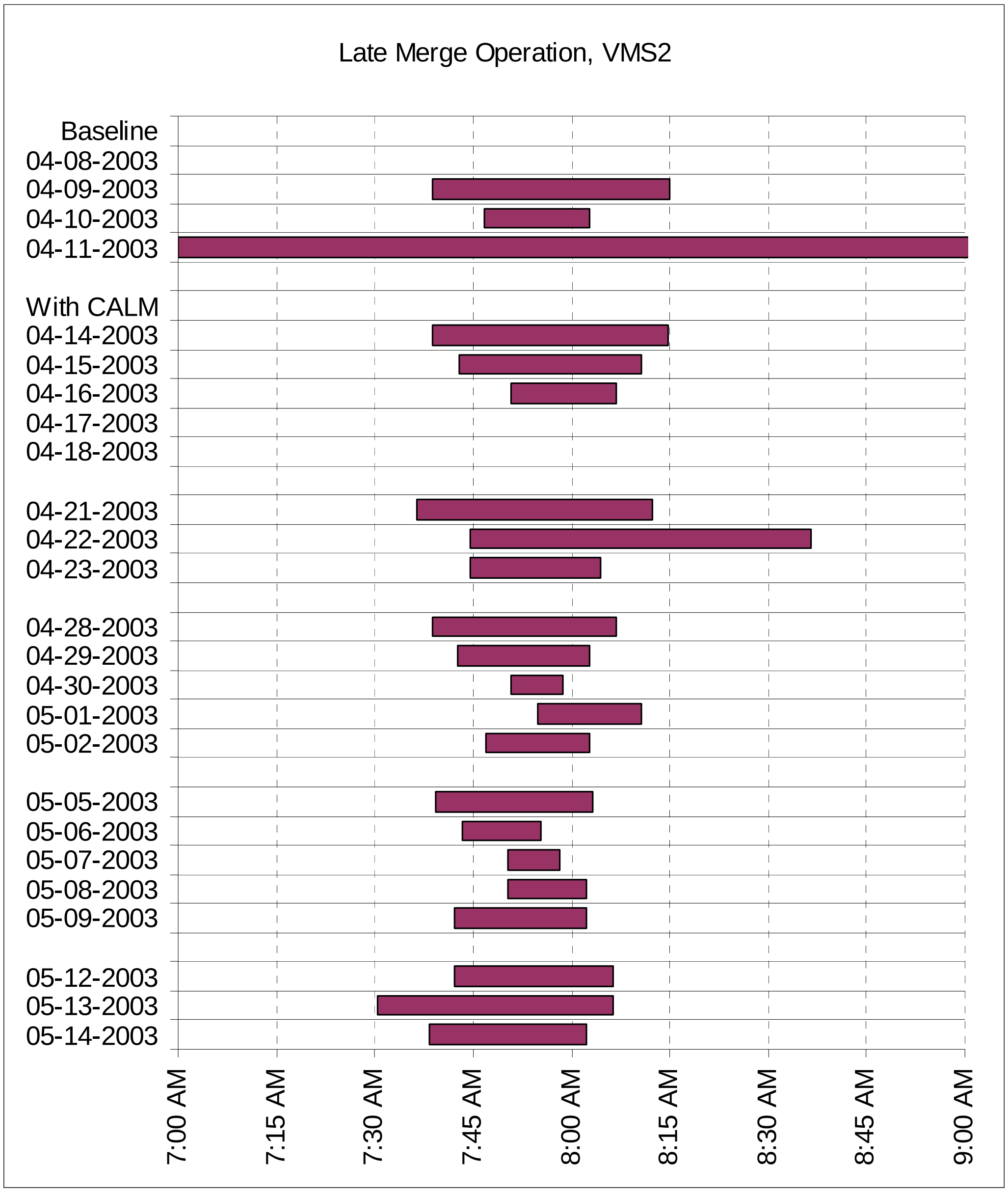

Percent Volume in Lane 1 by Overall Density Category, RTMS 5
Percent Volume in Lane 1
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
5
10
15
20
25*
30*
35
40*
45
50
120
Upper Bound of Density Category (pcpmpl)
before
after
(* indicates the difference is significant at a 95% confidence level)

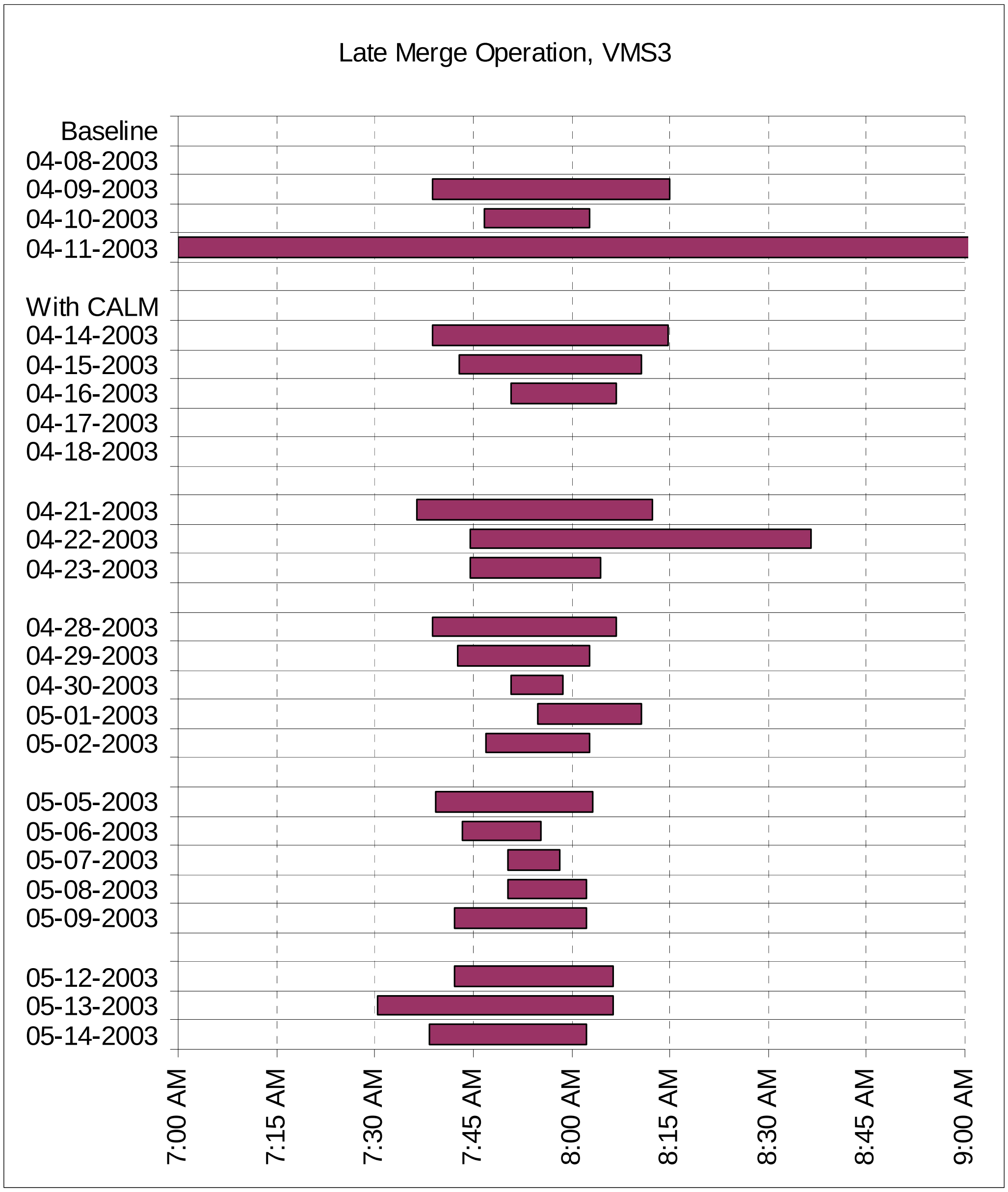

Percent Volume in Lane 1 by Overall Density Category, RTMS 6
Percent Volume in Lane 1
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
5
10
15
20
25*
30
35
40
45
50
120
Upper Bound of Density Category (pcpmpl)
before
after
(* indicates the difference is significant at a 95% confidence level)

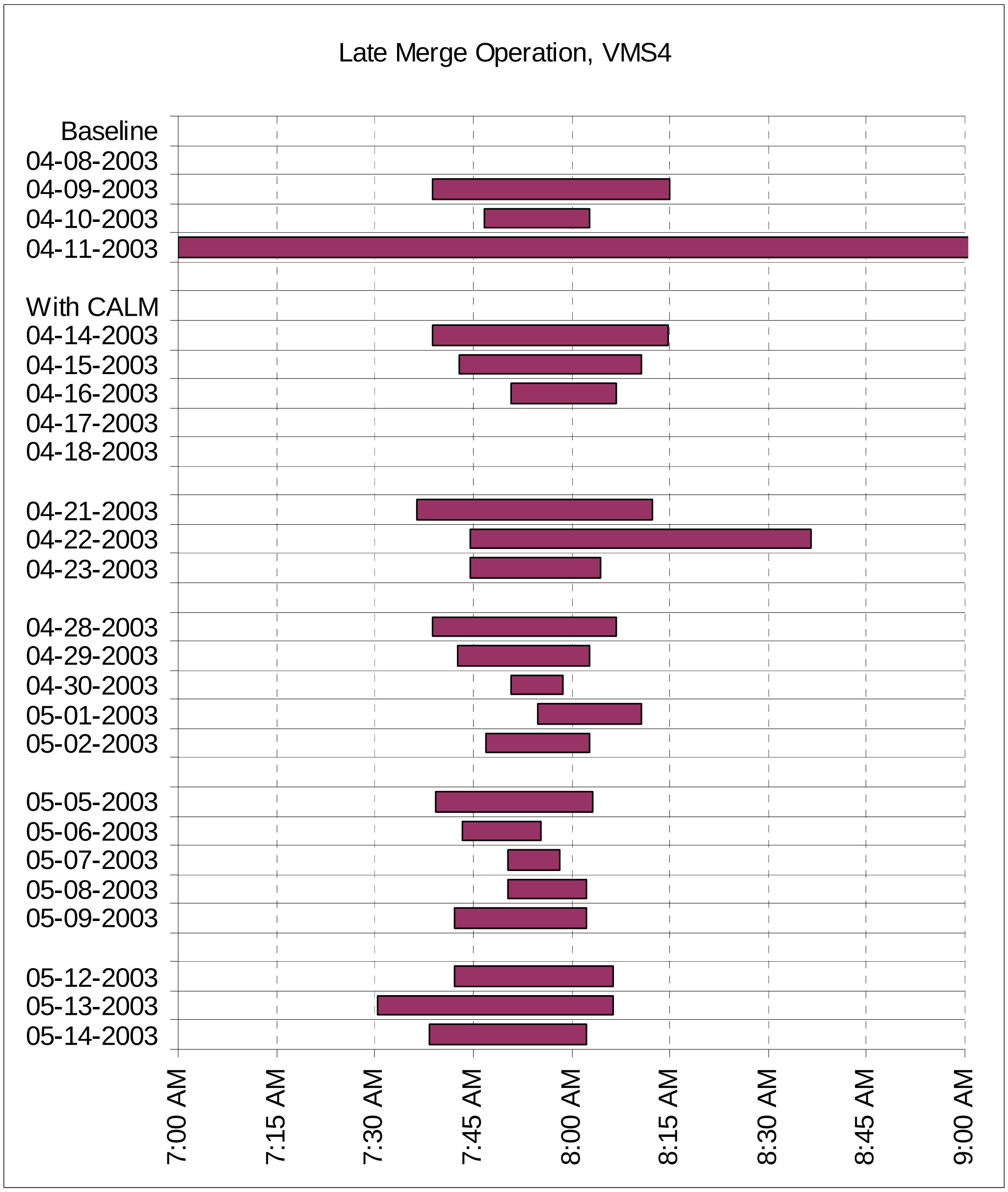
APPENDIX B

Operation Modes by VMS, Then by Day

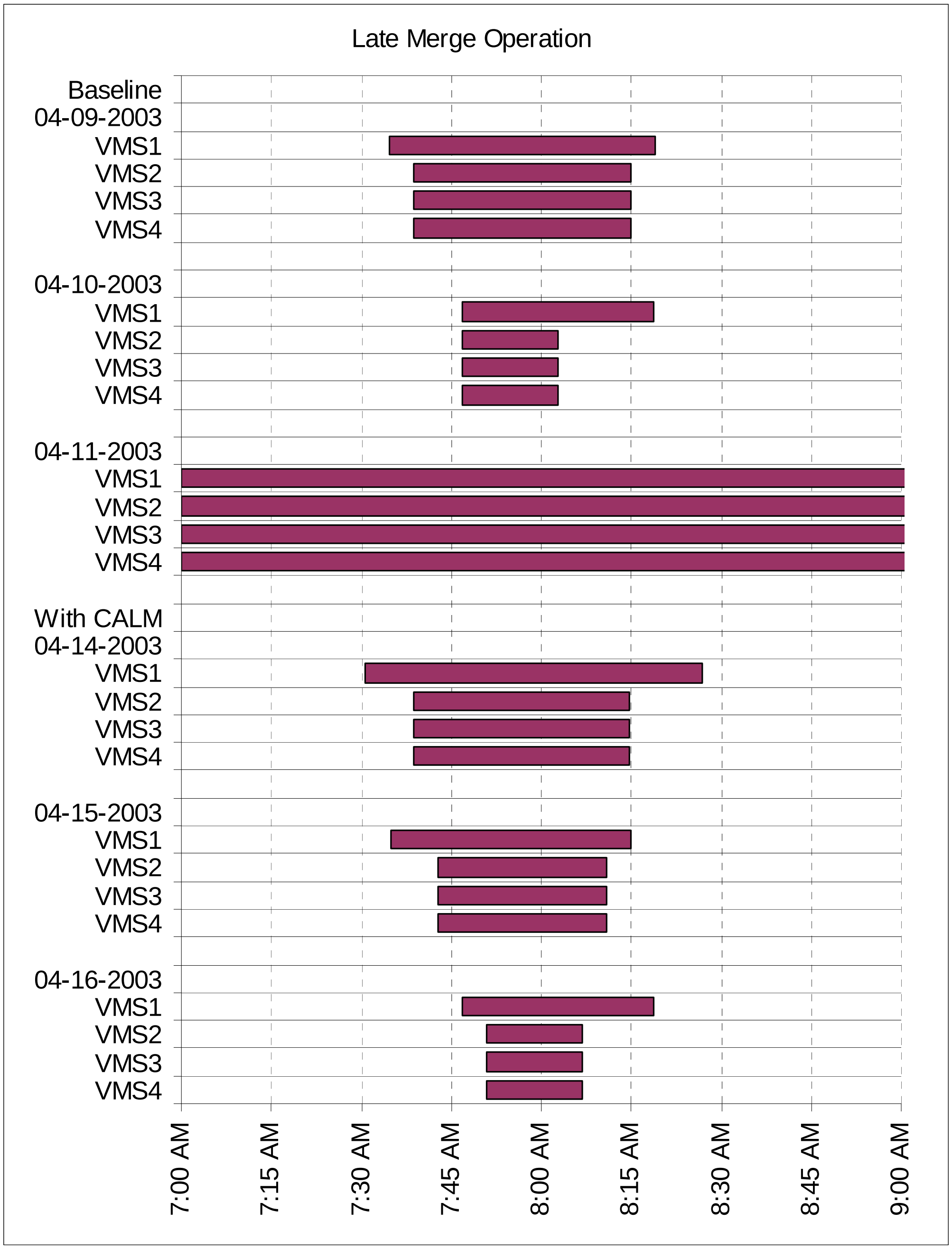


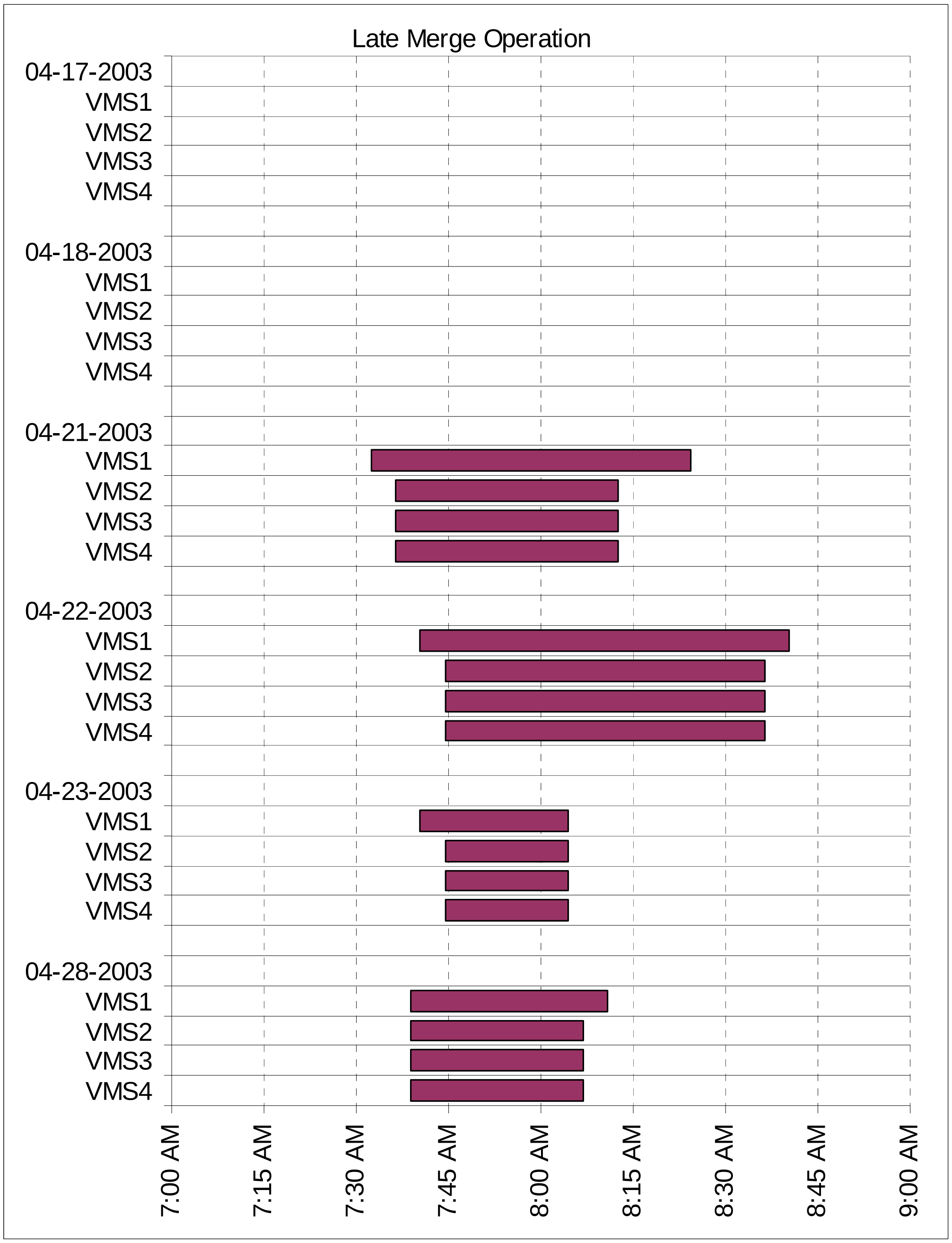

Late Merge Operation, VMS2
Baseline
04-08-2003
04-09-2003
04-10-2003
04-11-2003
With CALM
04-14-2003
04-15-2003
04-16-2003
04-17-2003
04-18-2003
04-21-2003
04-22-2003
04-23-2003
04-28-2003
04-29-2003
04-30-2003
05-01-2003
05-02-2003
05-05-2003
05-06-2003
05-07-2003
05-08-2003
05-09-2003
05-12-2003
05-13-2003
05-14-2003
7:00 AM
7:15 AM
7:30 AM
7:45 AM
8:00 AM
8:15 AM
8:30 AM
8:45 AM
9:00 AM

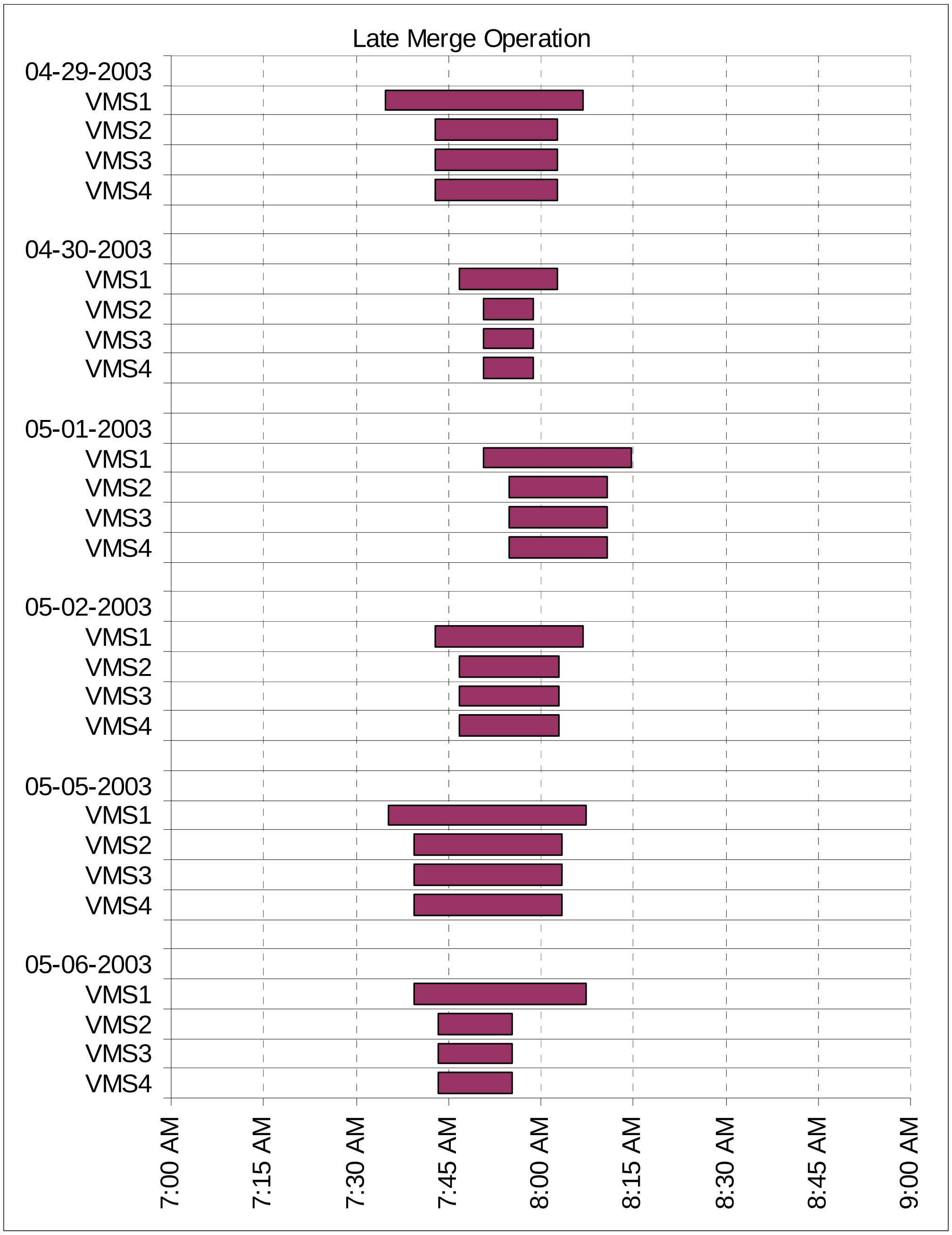

Late Merge Operation, VMS3
Baseline
04-08-2003
04-09-2003
04-10-2003
04-11-2003
With CALM
04-14-2003
04-15-2003
04-16-2003
04-17-2003
04-18-2003
04-21-2003
04-22-2003
04-23-2003
04-28-2003
04-29-2003
04-30-2003
05-01-2003
05-02-2003
05-05-2003
05-06-2003
05-07-2003
05-08-2003
05-09-2003
05-12-2003
05-13-2003
05-14-2003
7:00 AM
7:15 AM
7:30 AM
7:45 AM
8:00 AM
8:15 AM
8:30 AM
8:45 AM
9:00 AM

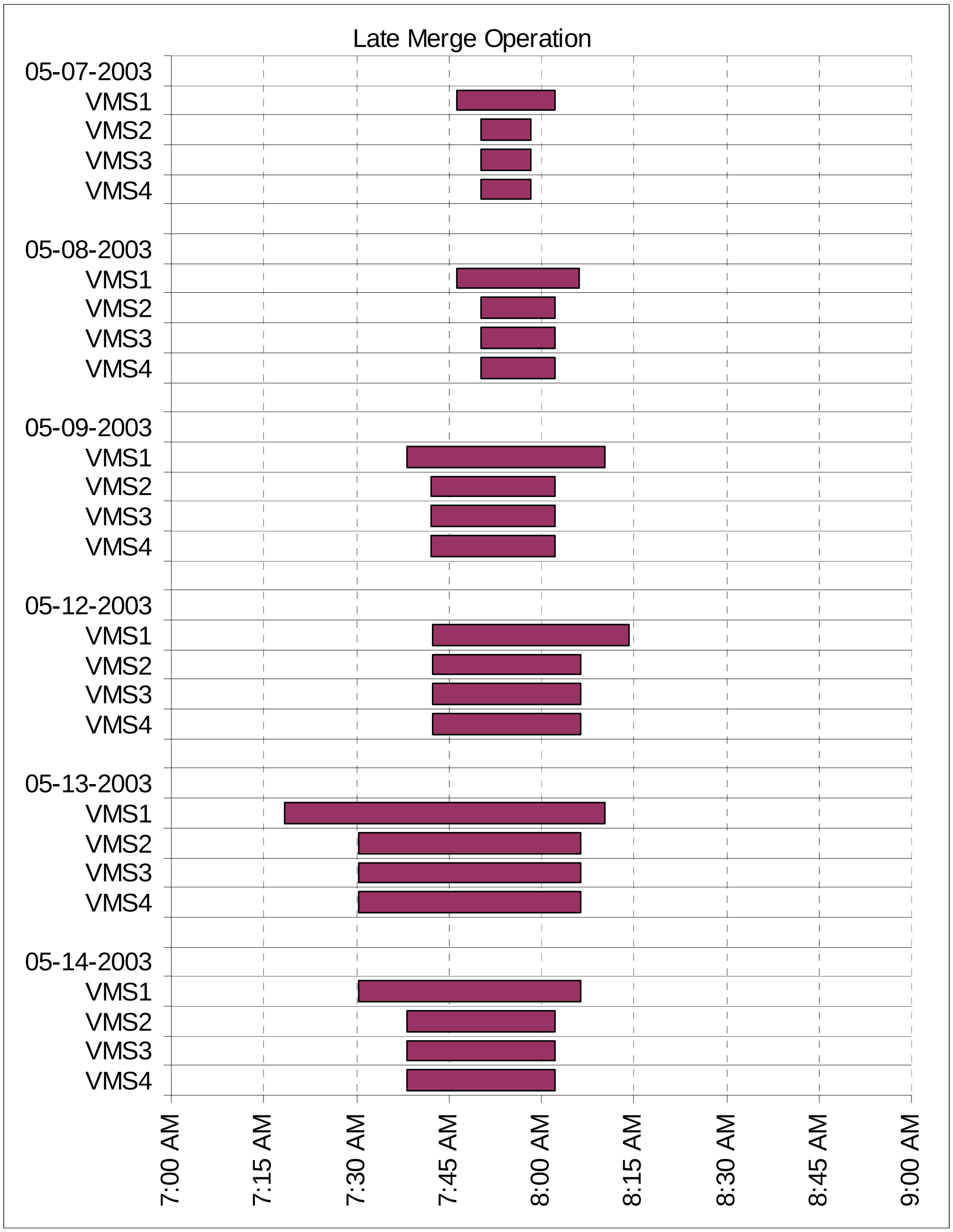

Late Merge Operation, VMS4
Baseline
04-08-2003
04-09-2003
04-10-2003
04-11-2003
With CALM
04-14-2003
04-15-2003
04-16-2003
04-17-2003
04-18-2003
04-21-2003
04-22-2003
04-23-2003
04-28-2003
04-29-2003
04-30-2003
05-01-2003
05-02-2003
05-05-2003
05-06-2003
05-07-2003
05-08-2003
05-09-2003
05-12-2003
05-13-2003
05-14-2003
7:00 AM
7:15 AM
7:30 AM
7:45 AM
8:00 AM
8:15 AM
8:30 AM
8:45 AM
9:00 AM

Operation Modes by Day, Then by VMS




Late Merge Operation
04-17-2003
VMS1
VMS2
VMS3
VMS4
04-18-2003
VMS1
VMS2
VMS3
VMS4
04-21-2003
VMS1
VMS2
VMS3
VMS4
04-22-2003
VMS1
VMS2
VMS3
VMS4
04-23-2003
VMS1
VMS2
VMS3
VMS4
04-28-2003
VMS1
VMS2
VMS3
VMS4
7:00 AM
7:15 AM
7:30 AM
7:45 AM
8:00 AM
8:15 AM
8:30 AM
8:45 AM
9:00 AM


Late Merge Operation
04-29-2003
VMS1
VMS2
VMS3
VMS4
04-30-2003
VMS1
VMS2
VMS3
VMS4
05-01-2003
VMS1
VMS2
VMS3
VMS4
05-02-2003
VMS1
VMS2
VMS3
VMS4
05-05-2003
VMS1
VMS2
VMS3
VMS4
05-06-2003
VMS1
VMS2
VMS3
VMS4
7:00 AM
7:15 AM
7:30 AM
7:45 AM
8:00 AM
8:15 AM
8:30 AM
8:45 AM
9:00 AM


Late Merge Operation
05-07-2003
VMS1
VMS2
VMS3
VMS4
05-08-2003
VMS1
VMS2
VMS3
VMS4
05-09-2003
VMS1
VMS2
VMS3
VMS4
05-12-2003
VMS1
VMS2
VMS3
VMS4
05-13-2003
VMS1
VMS2
VMS3
VMS4
05-14-2003
VMS1
VMS2
VMS3
VMS4
7:00 AM
7:15 AM
7:30 AM
7:45 AM
8:00 AM
8:15 AM
8:30 AM
8:45 AM
9:00 AM

APPENDIX C

Results from t-tests at RTMS 5 and RTMS 6

RTMS 5

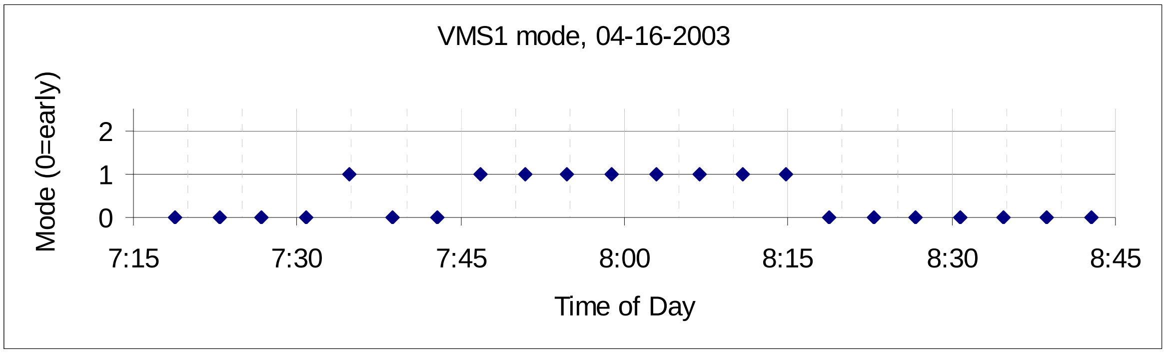
	Percent of Total Volume in Lane 1			Volume (vph)			Speed in Lane 2 (mph)		
All baseline vs All treatment		*Before*	*After*		*Before*	*After*		*Before*	*After*
	Mean	**0.077**	**0.100**	**Mean**	**3466**	**3468**	**Mean**	**33.2**	**29.6**
	Variance	0.001	0.003	Variance	107204	111599	Variance	186.6	337.9
	Observations	17	82	Observations	17	82	Observations	17	82
	df	35		df	23		df	29	
	t Stat	-2.322		t Stat	-0.022		t Stat	0.933	
	P(T<=t) two-tail	**0.026**		**P(T<=t) two-tail**	**0.983**		**P(T<=t) two-tail**	**0.358**	
	t Critical two-tail	2.030		t Critical two-tail	2.069		t Critical two-tail	2.045	
All baseline vs Week 1 treatment		*Before*	*Week 1*		*Before*	*Week 1*		*Before*	*Week 1*
	Mean	**0.077**	**0.063**	**Mean**	**3466**	**3329**	**Mean**	**33.2**	**36.2**
	Variance	0.001	0.001	Variance	107204	167768	Variance	186.6	375.3
	Observations	17	24	Observations	17	24	Observations	17	24
	df	37		df	38		df	39	
	t Stat	1.248		t Stat	1.192		t Stat	-0.576	
	P(T<=t) two-tail	**0.220**		**P(T<=t) two-tail**	**0.241**		**P(T<=t) two-tail**	**0.568**	
	t Critical two-tail	2.026		t Critical two-tail	2.024		t Critical two-tail	2.023	
Week 1 treatment vs Week 2 and forward		*Week 1*	*Week 2*		*Week 1*	*Week 2*		*Week 1*	*Week 2*
	Mean	**0.063**	**0.115**	**Mean**	**3329**	**3526**	**Mean**	**36.2**	**26.9**
	Variance	0.001	0.003	Variance	167768	79329	Variance	375.3	302.8
	Observations	24	58	Observations	24	58	Observations	24	58
	df	60		df	32		df	39	
	t Stat	-5.164		t Stat	-2.155		t Stat	2.043	
	P(T<=t) two-tail	**0.000**		**P(T<=t) two-tail**	**0.039**		**P(T<=t) two-tail**	**0.048**	
	t Critical two-tail	2.000		t Critical two-tail	2.037		t Critical two-tail	2.023	
All baseline vs Week 2 treatment and forward		*Before*	*Week 2*		*Before*	*Week 2*		*Before*	*Week 2*
	Mean	**0.077**	**0.115**	**Mean**	**3466**	**3526**	**Mean**	**33.2**	**26.9**
	Variance	0.001	0.003	Variance	107204	79329	Variance	186.6	302.8
	Observations	17	58	Observations	17	58	Observations	17	58
	df	41		df	23		df	33	
	t Stat	-3.648		t Stat	-0.680		t Stat	1.579	
	P(T<=t) two-tail	**0.001**		**P(T<=t) two-tail**	**0.503**		**P(T<=t) two-tail**	**0.124**	
	t Critical two-tail	2.020		t Critical two-tail	2.069		t Critical two-tail	2.035	

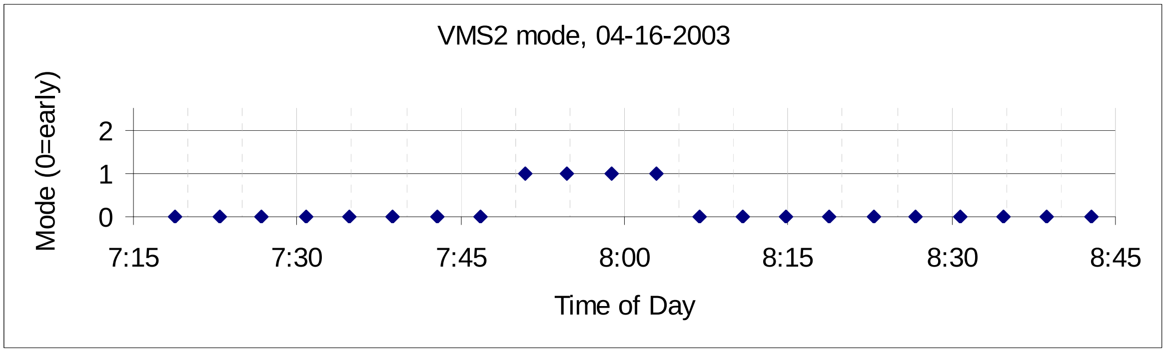
RTMS 6

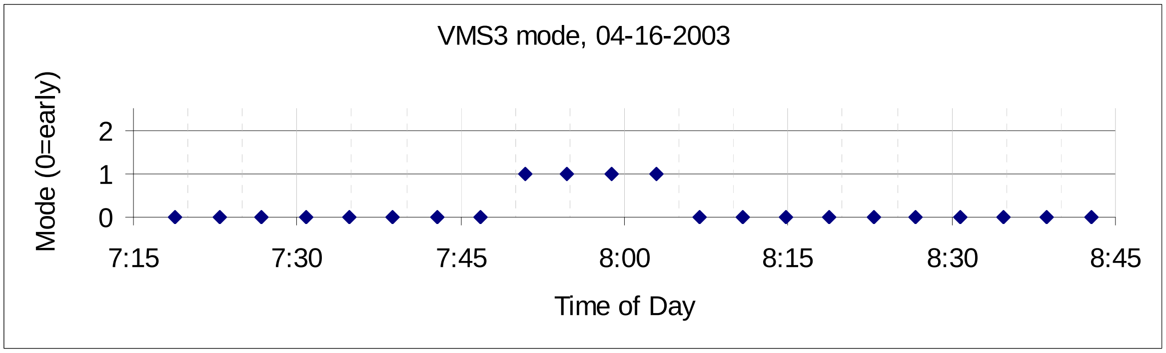
	Percent of Total Volume in Lane 1			Volume (vph)			Speed in Lane 2 (mph)		
All baseline vs All treatment		*Before*	*After*		*Before*	*After*		*Before*	*After*
	Mean	**0.139**	**0.163**	**Mean**	**3197**	**3473**	**Mean**	**44.3**	**37.5**
	Variance	0.001	0.002	Variance	345758	414127	Variance	336.0	317.6
	Observations	19	82	Observations	19	82	Observations	19	82
	df	40		df	29		df	26	
	t Stat	-2.779		t Stat	-1.810		t Stat	1.467	
	P(T<=t) two-tail	**0.008**		**P(T<=t) two-tail**	**0.081**		**P(T<=t) two-tail**	**0.154**	
	t Critical two-tail	2.021		t Critical two-tail	2.045		t Critical two-tail	2.056	
All baseline vs Week 1 treatment		*Before*	*Week 1*		*Before*	*Week 1*		*Before*	*Week 1*
	Mean	**0.139**	**0.161**	**Mean**	**3197**	**3557**	**Mean**	**44.3**	**36.0**
	Variance	0.001	0.001	Variance	345758	283254	Variance	336.0	303.4
	Observations	19	24	Observations	19	24	Observations	19	24
	df	41		df	37		df	38	
	t Stat	-2.230		t Stat	-2.076		t Stat	1.508	
	P(T<=t) two-tail	**0.031**		**P(T<=t) two-tail**	**0.045**		**P(T<=t) two-tail**	**0.140**	
	t Critical two-tail	2.020		t Critical two-tail	2.026		t Critical two-tail	2.024	
Week 1 treatment vs Week 2 and forward		*Week 1*	*Week 2*		*Week 1*	*Week 2*		*Week 1*	*Week 2*
	Mean	**0.161**	**0.163**	**Mean**	**3557**	**3438**	**Mean**	**36.0**	**38.1**
	Variance	0.001	0.002	Variance	283254	470033	Variance	303.4	327.6
	Observations	24	58	Observations	24	58	Observations	24	58
	df	59		df	55		df	45	
	t Stat	-0.201		t Stat	0.838		t Stat	-0.494	
	P(T<=t) two-tail	**0.841**		**P(T<=t) two-tail**	**0.405**		**P(T<=t) two-tail**	**0.624**	
	t Critical two-tail	2.001		t Critical two-tail	2.004		t Critical two-tail	2.014	
All baseline vs Week 2 treatment and forward		*Before*	*Week 2*		*Before*	*Week 2*		*Before*	*Week 2*
	Mean	**0.139**	**0.163**	**Mean**	**3197**	**3438**	**Mean**	**44.3**	**38.1**
	Variance	0.001	0.002	Variance	345758	470033	Variance	336.0	327.6
	Observations	19	58	Observations	19	58	Observations	19	58
	df	51		df	35		df	30	
	t Stat	-2.567		t Stat	-1.488		t Stat	1.282	
	P(T<=t) two-tail	**0.013**		**P(T<=t) two-tail**	**0.146**		**P(T<=t) two-tail**	**0.210**	
	t Critical two-tail	2.008		t Critical two-tail	2.030		t Critical two-tail	2.042	

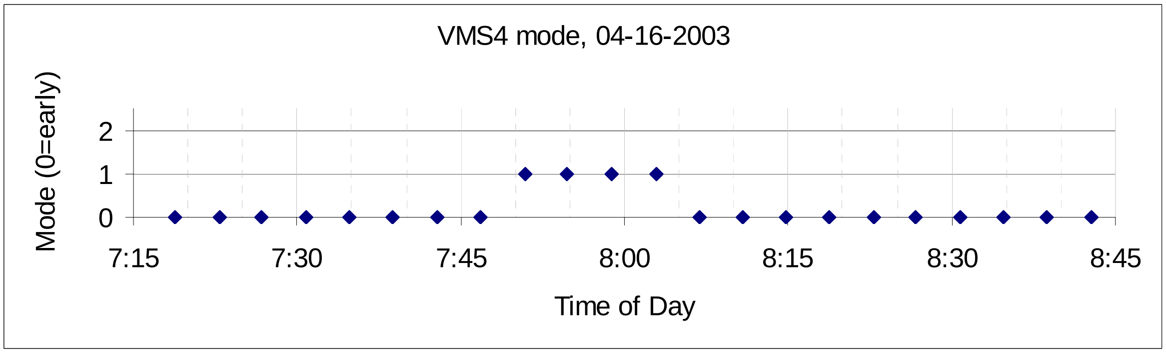
APPENDIX D

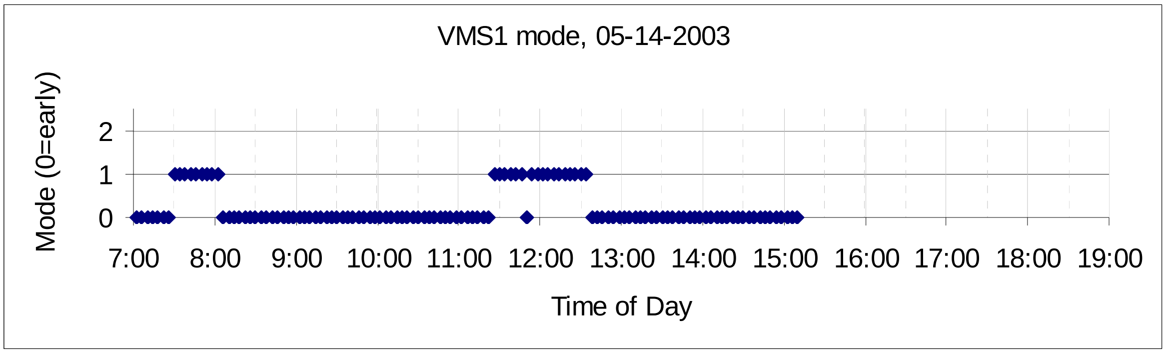
Days With Unusual Operation Mode Characteristics

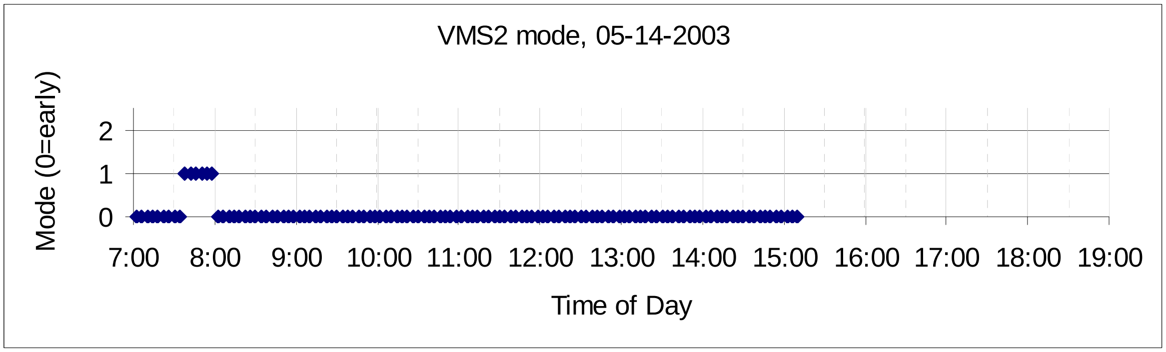


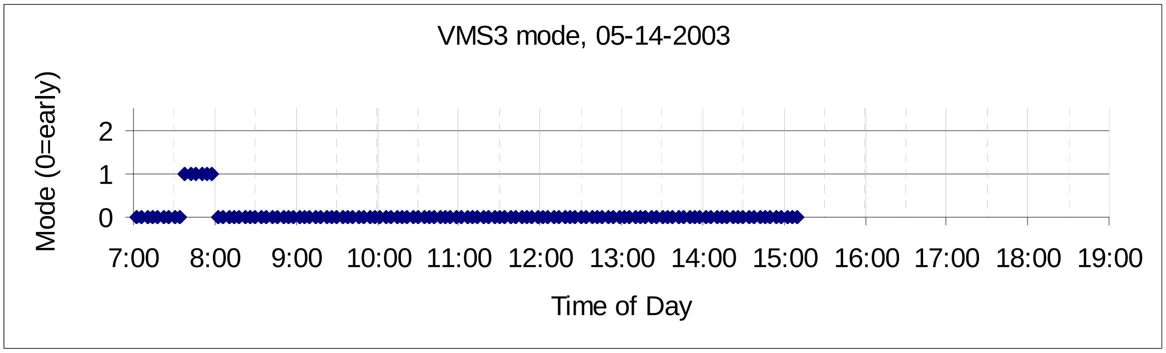


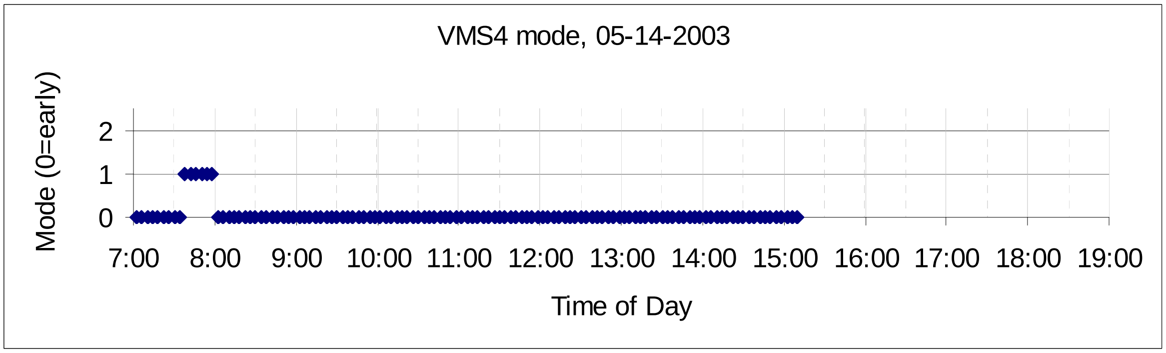


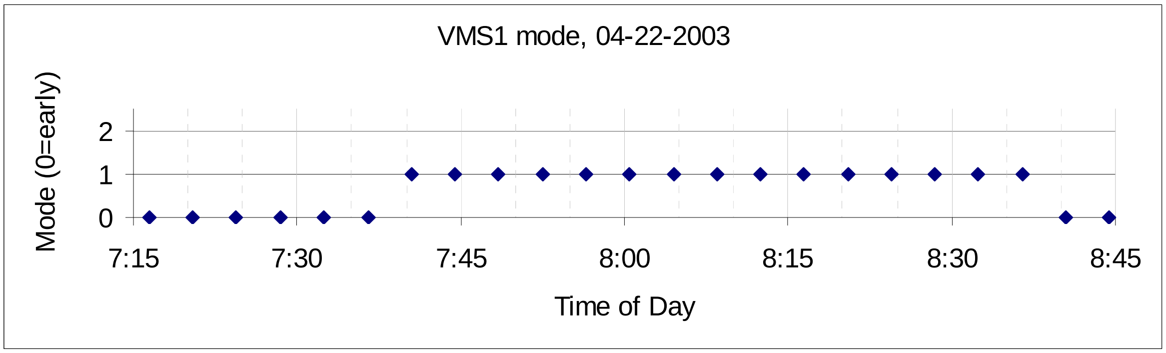


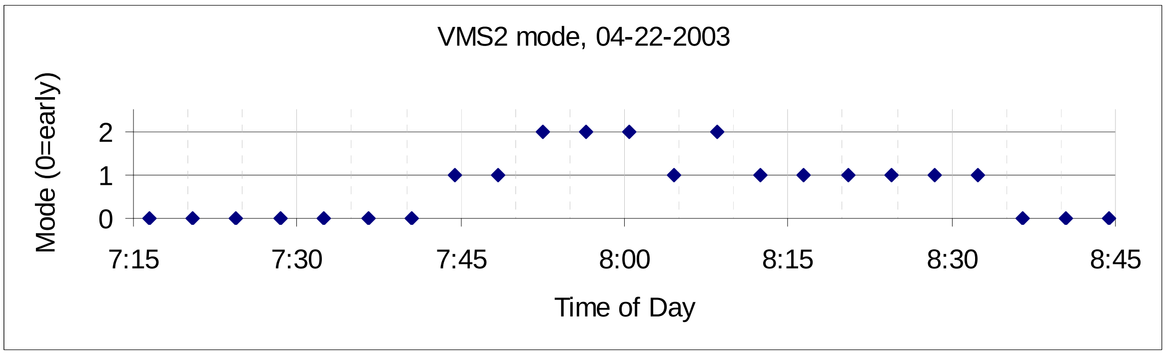

VMS1 mode, 05-14-2003
Mode (0=early)
2
1
0
7:00
8:00
9:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
18:00
19:00
Time of Day

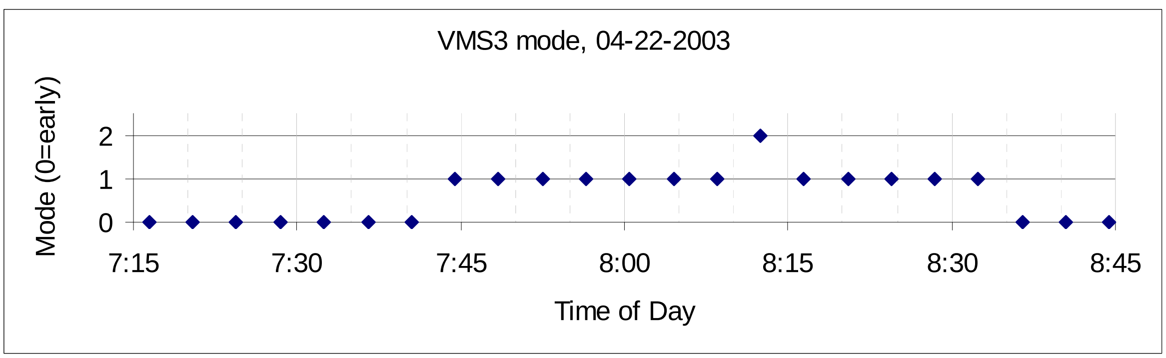

VMS2 mode, 05-14-2003
Mode (0=early)
2
1
0
7:00
8:00
9:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
18:00
19:00
Time of Day

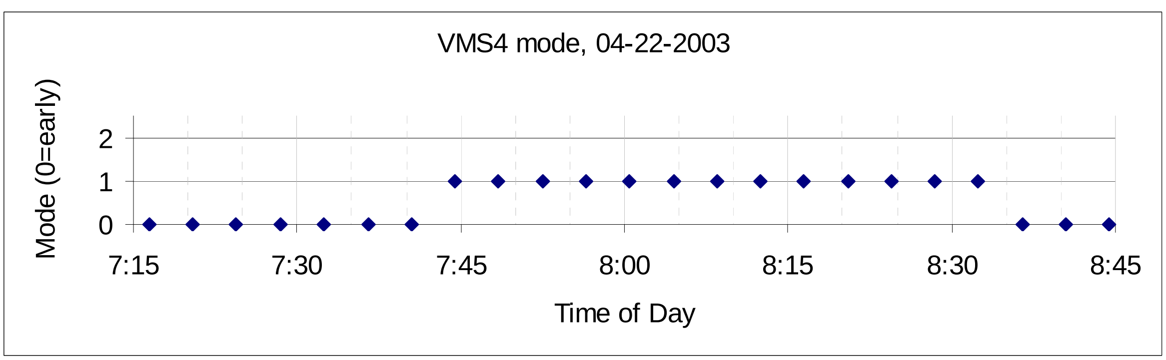

VMS3 mode, 05-14-2003
Mode (0=early)
2
1
0
7:00
8:00
9:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
18:00
19:00
Time of Day

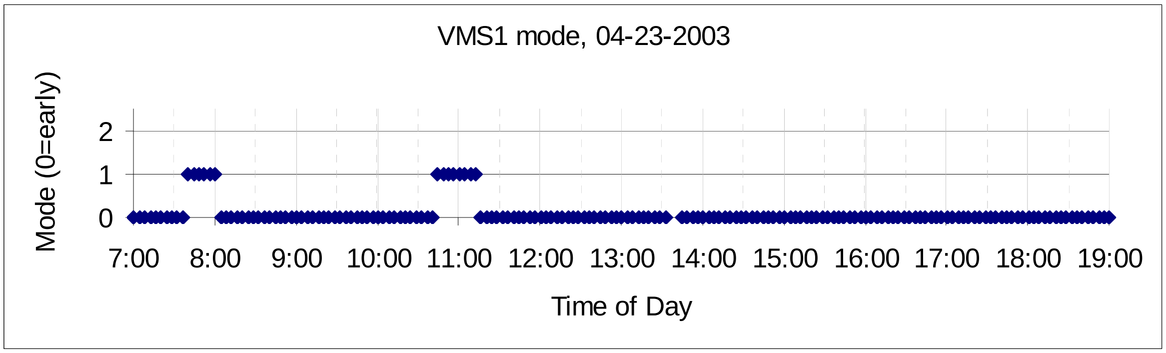

VMS4 mode, 05-14-2003
Mode (0=early)
2
1
0
7:00
8:00
9:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
18:00
19:00
Time of Day

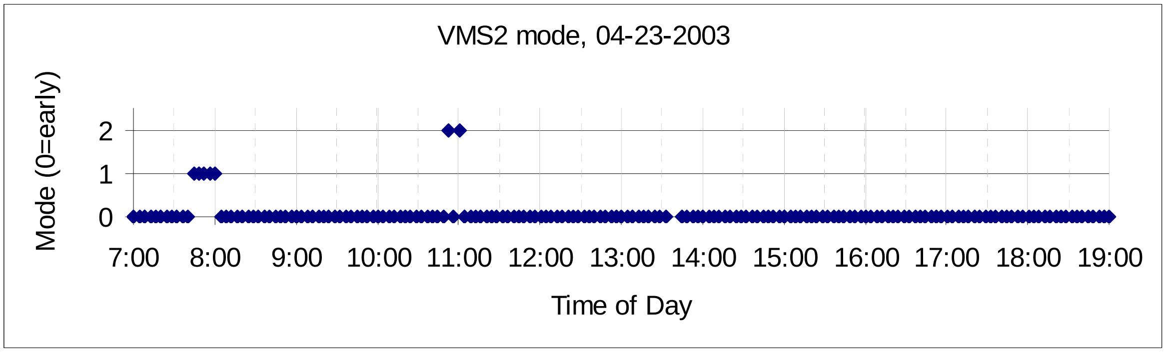

VMS1 mode, 04-22-2003
Mode (0=early)
2
1
0
7:15
7:30
7:45
8:00
8:15
8:30
8:45
Time of Day


VMS2 mode, 04-22-2003
Mode (0=early)
2
1
0
7:15
7:30
7:45
8:00
8:15
8:30
8:45
Time of Day


VMS3 mode, 04-22-2003
Mode (0=early)
2
1
0
7:15
7:30
7:45
8:00
8:15
8:30
8:45
Time of Day


VMS4 mode, 04-22-2003
Mode (0=early)
2
1
0
7:15
7:30
7:45
8:00
8:15
8:30
8:45
Time of Day


VMS1 mode, 04-23-2003
Mode (0=early)
2
1
0
7:00 8:00 9:00 10:00 11:00 12:00 13:00 14:00 15:00 16:00 17:00 18:00 19:00
Time of Day


VMS2 mode, 04-23-2003
Mode (0=early)
2
1
0
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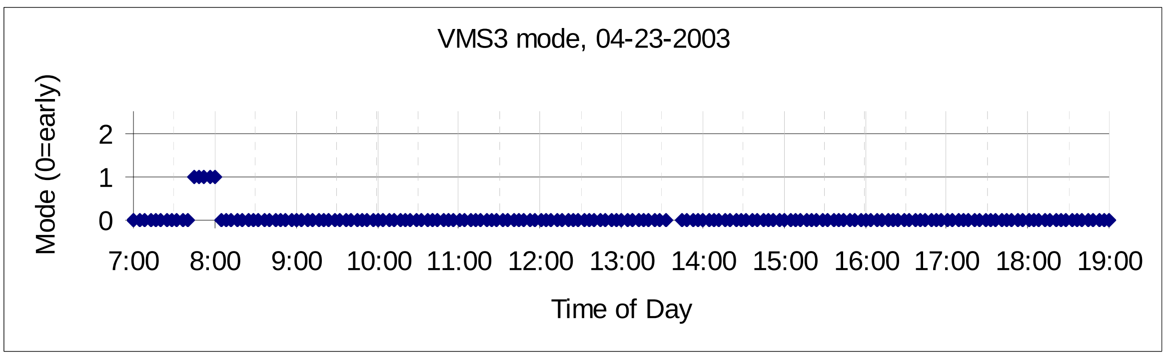
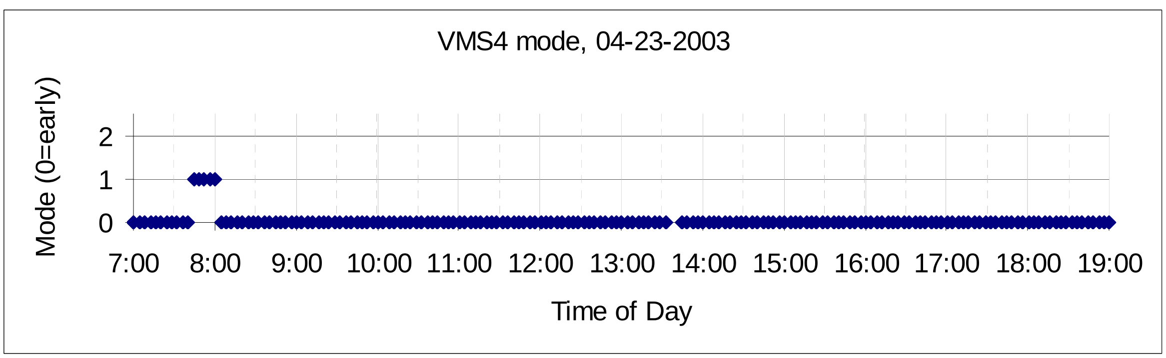
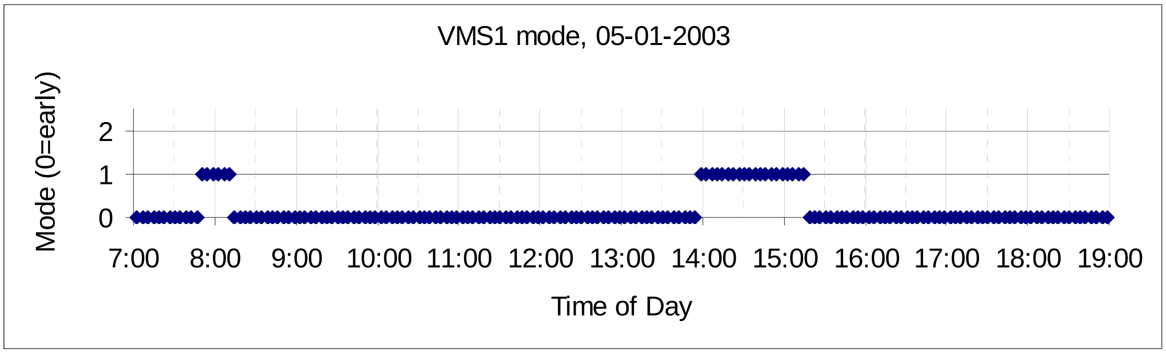
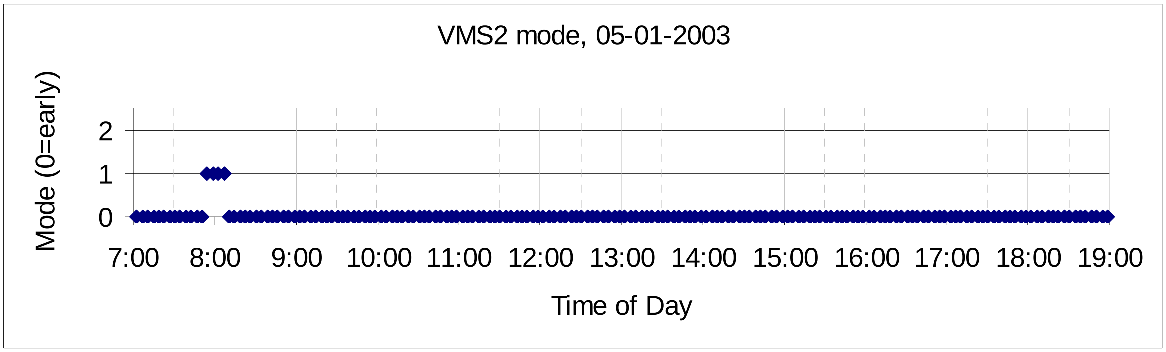
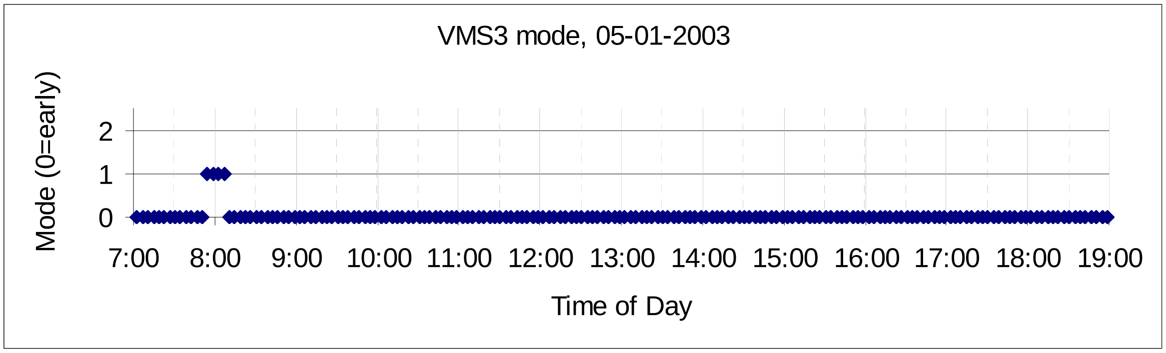
Time of Day

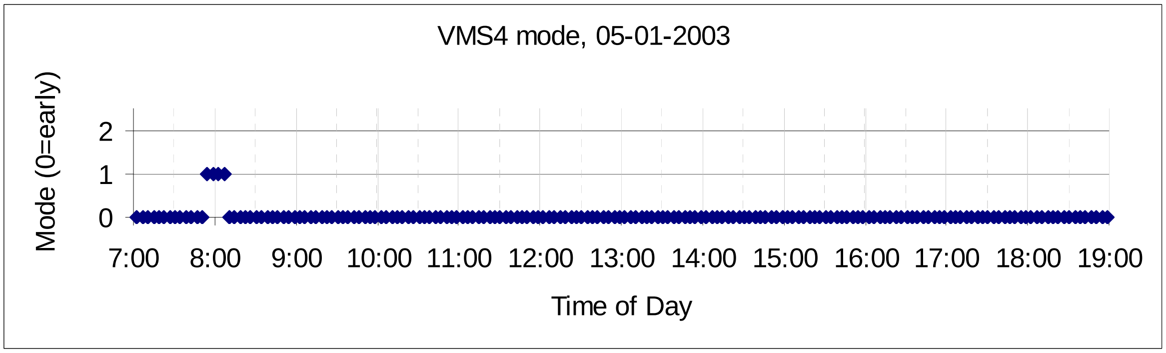

VMS3 mode, 04-23-2003
Mode (0=early)
2
1
0
7:00 8:00 9:00 10:00 11:00 12:00 13:00 14:00 15:00 16:00 17:00 18:00 19:00
Time of Day

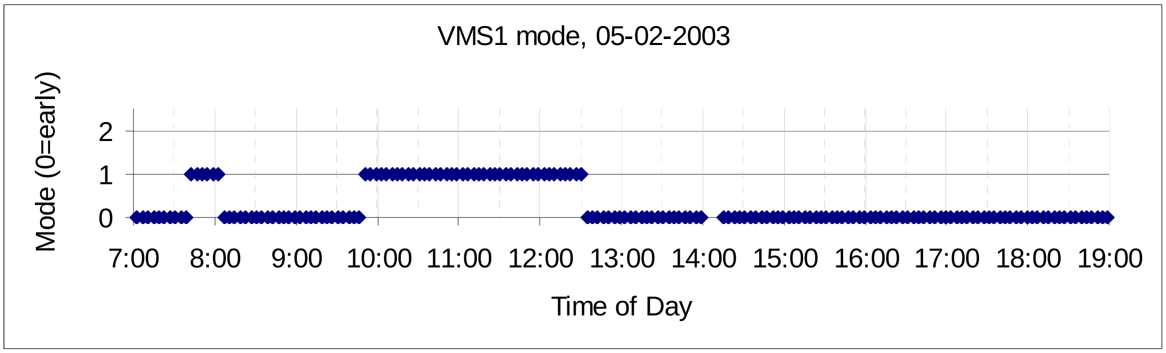

VMS4 mode, 04-23-2003
Mode (0=early)
2
1
0
7:00 8:00 9:00 10:00 11:00 12:00 13:00 14:00 15:00 16:00 17:00 18:00 19:00
Time of Day


VMS1 mode, 05-01-2003
Mode (0=early)
2
1
0
7:00 8:00 9:00 10:00 11:00 12:00 13:00 14:00 15:00 16:00 17:00 18:00 19:00
Time of Day


VMS2 mode, 05-01-2003
Mode (0=early)
2
1
0
7:00 8:00 9:00 10:00 11:00 12:00 13:00 14:00 15:00 16:00 17:00 18:00 19:00
Time of Day


VMS3 mode, 05-01-2003
Mode (0=early)
2
1
0
7:00 8:00 9:00 10:00 11:00 12:00 13:00 14:00 15:00 16:00 17:00 18:00 19:00
Time of Day


VMS4 mode, 05-01-2003
Mode (0=early)
2
1
0
7:00 8:00 9:00 10:00 11:00 12:00 13:00 14:00 15:00 16:00 17:00 18:00 19:00
Time of Day


VMS1 mode, 05-02-2003
Mode (0=early)
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1
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7:00
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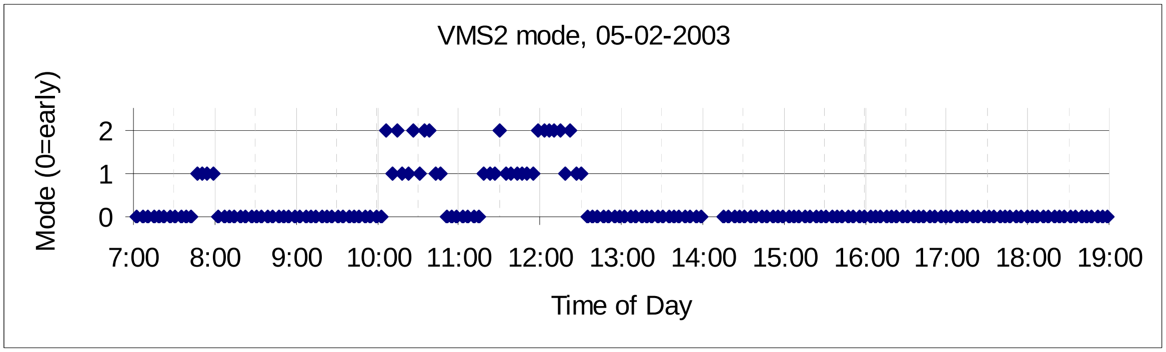
Time of Day


VMS2 mode, 05-02-2003
Mode (0=early)
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1
0
7:00
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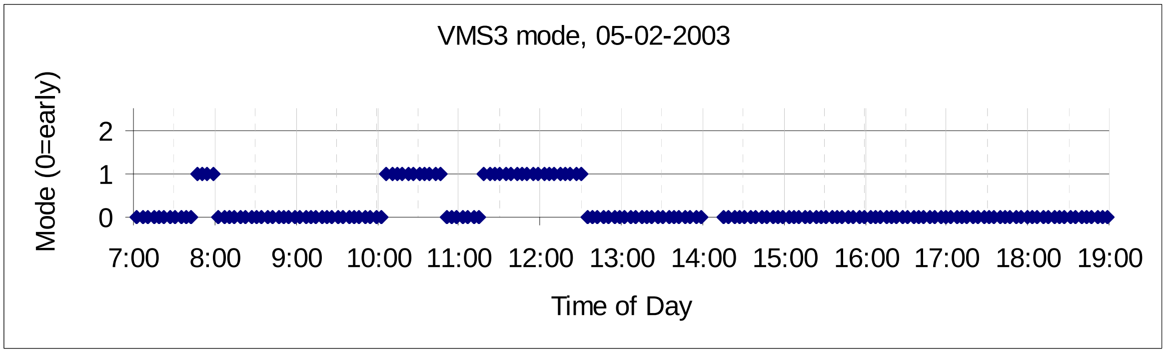
Time of Day


VMS3 mode, 05-02-2003
Mode (0=early)
2
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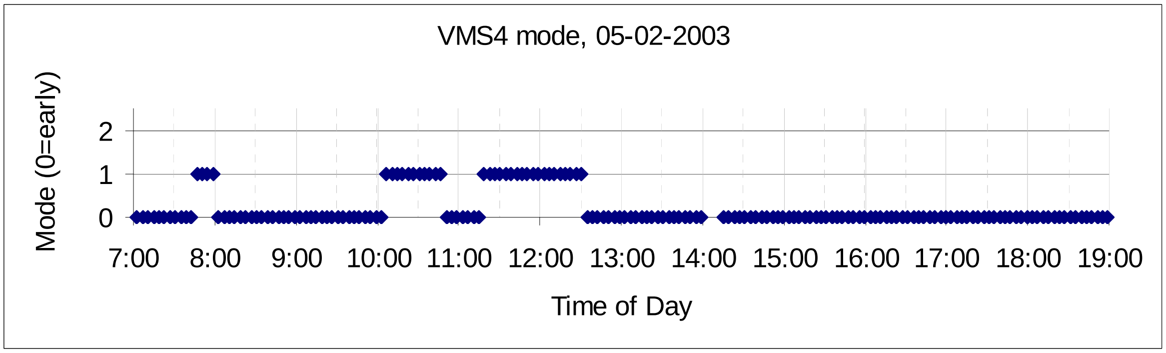
19:00
Time of Day


VMS4 mode, 05-02-2003
Mode (0=early)
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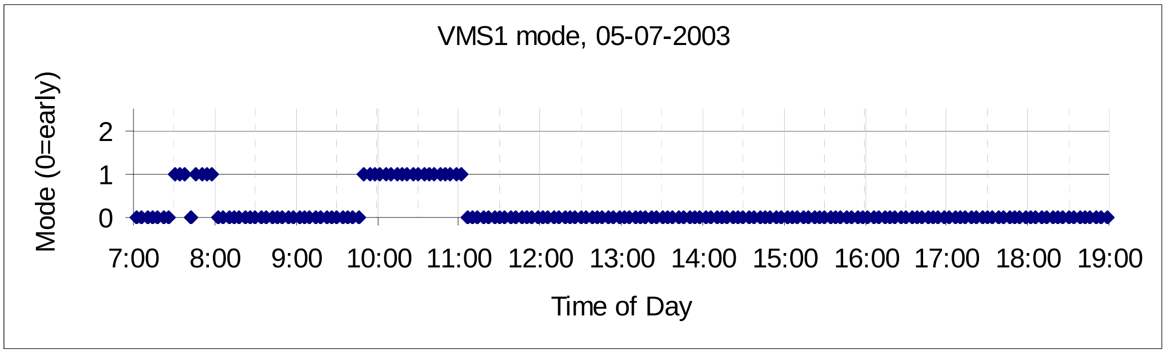
Time of Day


VMS1 mode, 05-07-2003
Mode (0=early)
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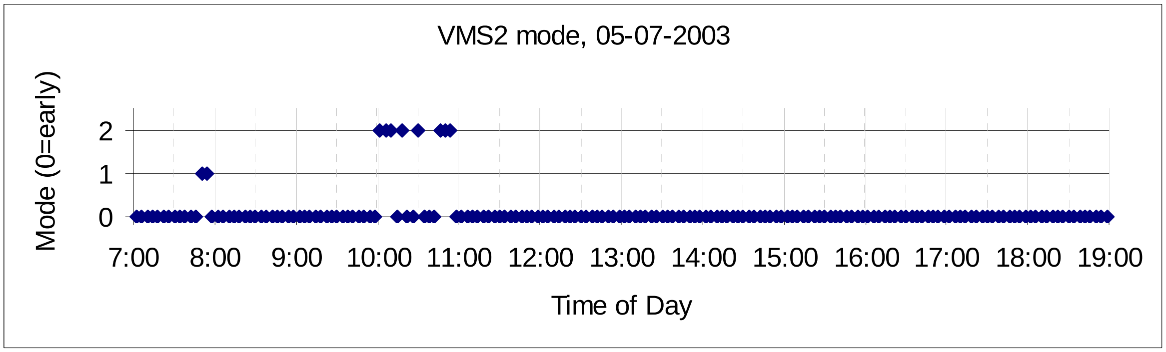
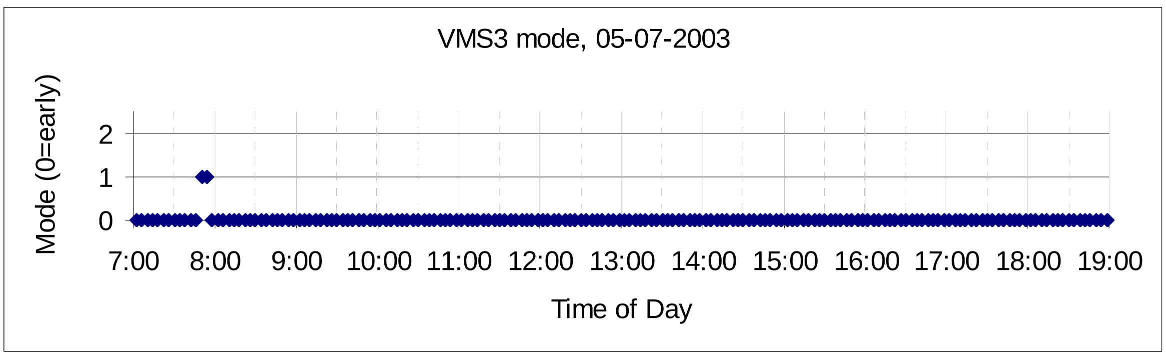
1
0
7:00 8:00 9:00 10:00 11:00 12:00 13:00 14:00 15:00 16:00 17:00 18:00 19:00
Time of Day


VMS2 mode, 05-07-2003
Mode (0=early)
2
1
0
7:00 8:00 9:00 10:00 11:00 12:00 13:00 14:00 15:00 16:00 17:00 18:00 19:00
Time of Day


VMS3 mode, 05-07-2003
Mode (0=early)
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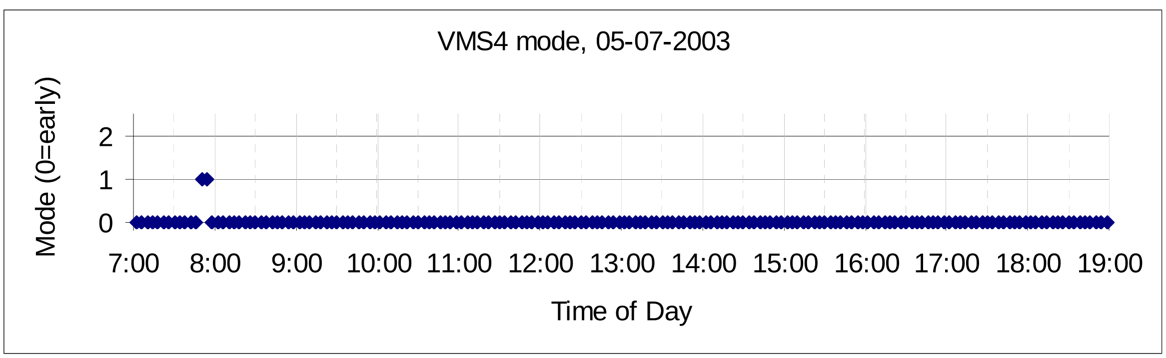
0
7:00 8:00 9:00 10:00 11:00 12:00 13:00 14:00 15:00 16:00 17:00 18:00 19:00
Time of Day


VMS4 mode, 05-07-2003
Mode (0=early)
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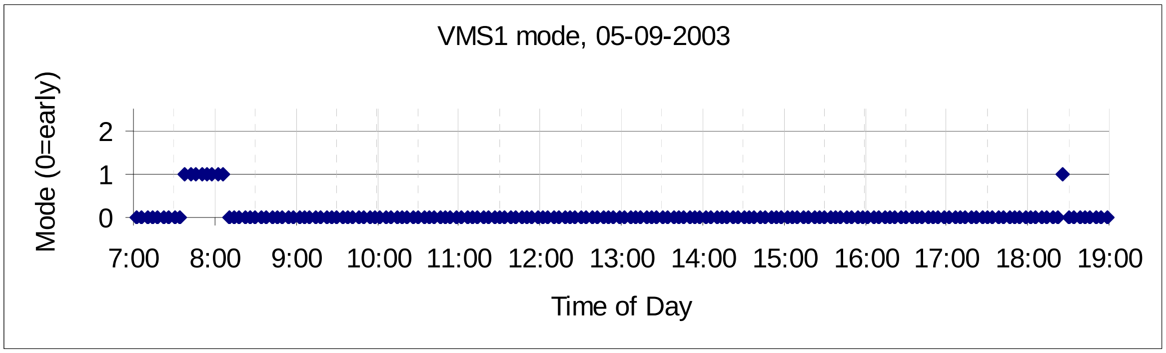
0
7:00 8:00 9:00 10:00 11:00 12:00 13:00 14:00 15:00 16:00 17:00 18:00 19:00
Time of Day


VMS1 mode, 05-09-2003
Mode (0=early)
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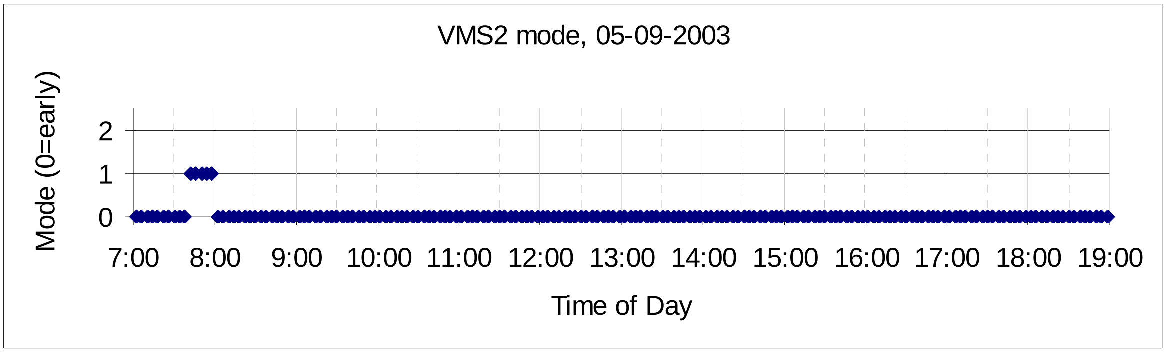
0
7:00 8:00 9:00 10:00 11:00 12:00 13:00 14:00 15:00 16:00 17:00 18:00 19:00
Time of Day


VMS2 mode, 05-09-2003
Mode (0=early)
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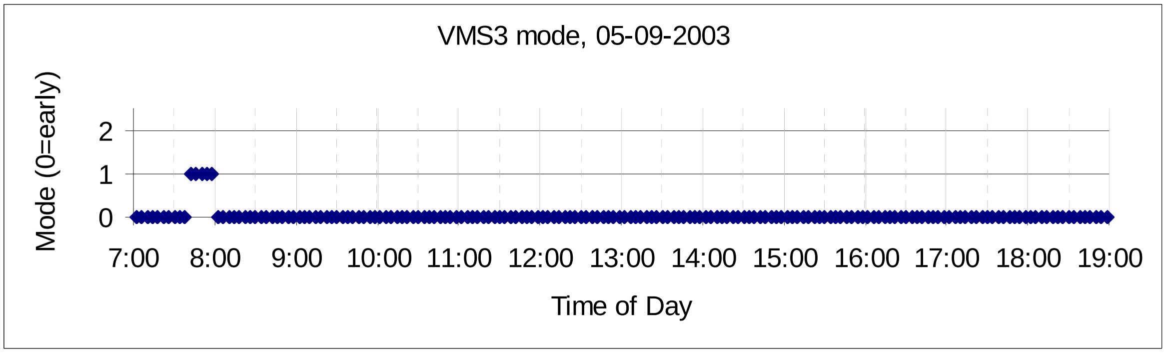
0
7:00 8:00 9:00 10:00 11:00 12:00 13:00 14:00 15:00 16:00 17:00 18:00 19:00
Time of Day


VMS3 mode, 05-09-2003
Mode (0=early)
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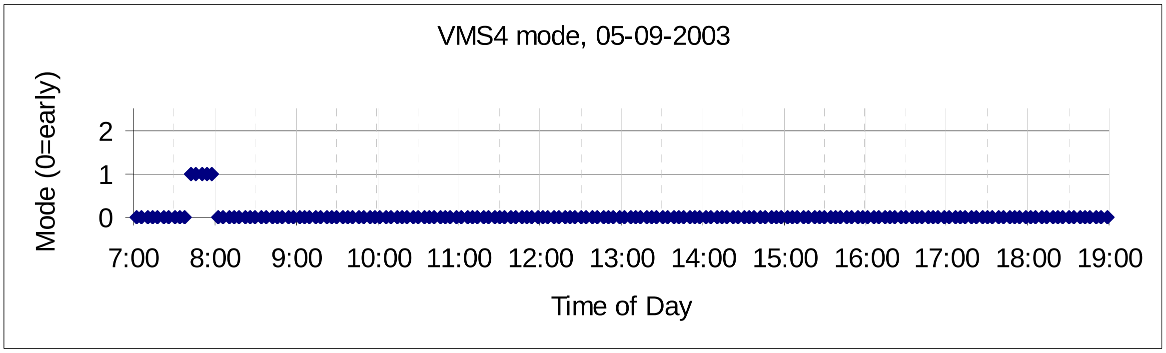
0
7:00 8:00 9:00 10:00 11:00 12:00 13:00 14:00 15:00 16:00 17:00 18:00 19:00
Time of Day


VMS4 mode, 05-09-2003
Mode (0=early)
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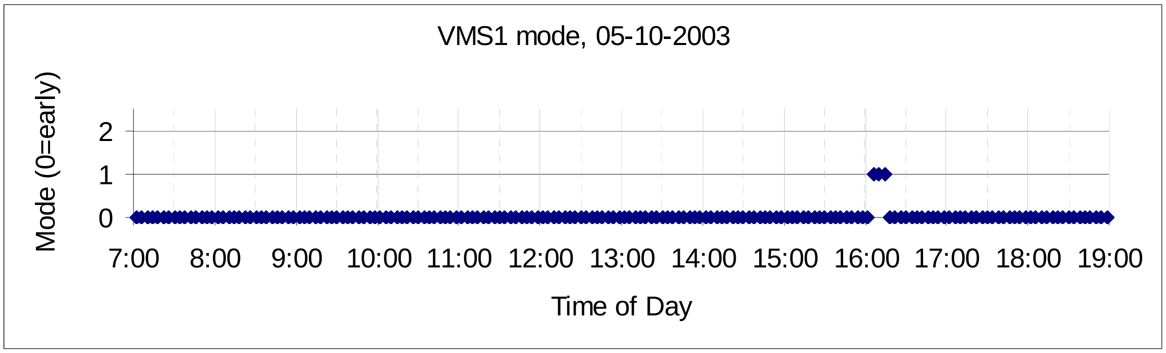
0
7:00 8:00 9:00 10:00 11:00 12:00 13:00 14:00 15:00 16:00 17:00 18:00 19:00
Time of Day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Mode (0=early)
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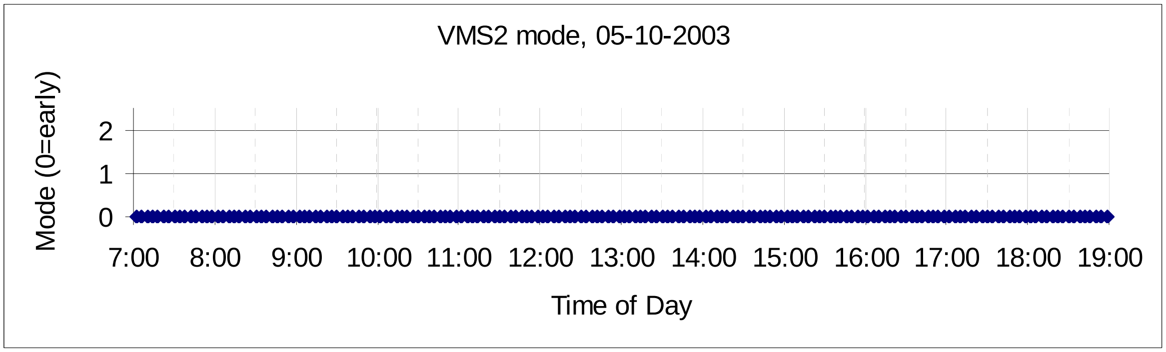
7:00 8:00 9:00 10:00 11:00 12:00 13:00 14:00 15:00 16:00 17:00 18:00 19:00
Time of Day


VMS2 mode, 05-10-2003
Mode (0=early)
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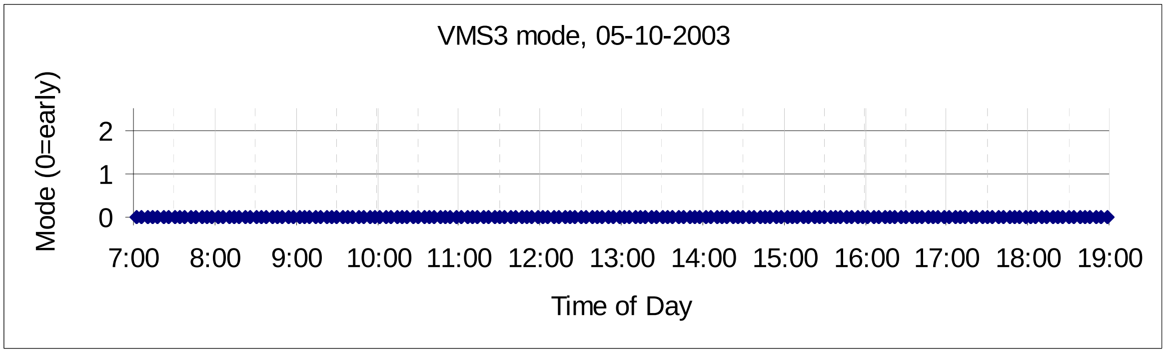
7:00 8:00 9:00 10:00 11:00 12:00 13:00 14:00 15:00 16:00 17:00 18:00 19:00
Time of Day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Mode (0=early)
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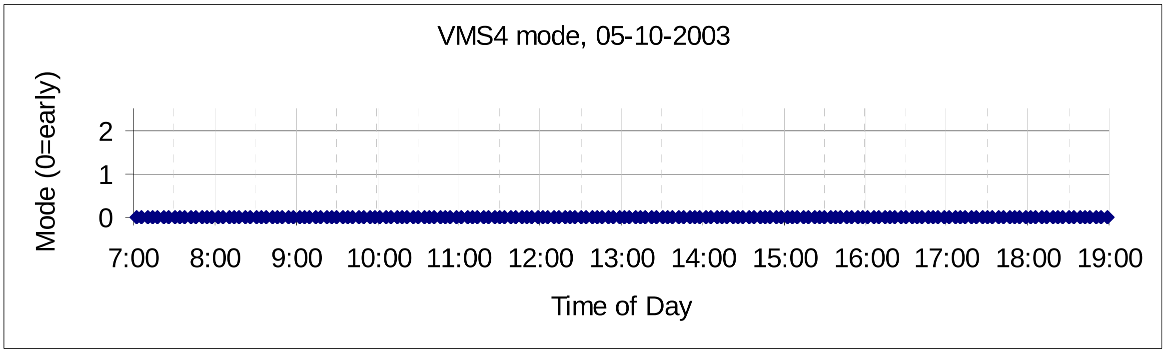
7:00 8:00 9:00 10:00 11:00 12:00 13:00 14:00 15:00 16:00 17:00 18:00 19:00
Time of Day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Mode (0=early)
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Time of Day