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Construction Area Late Merge (CALM) System

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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.

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Construction Area Late Merge (CALM)

System

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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.

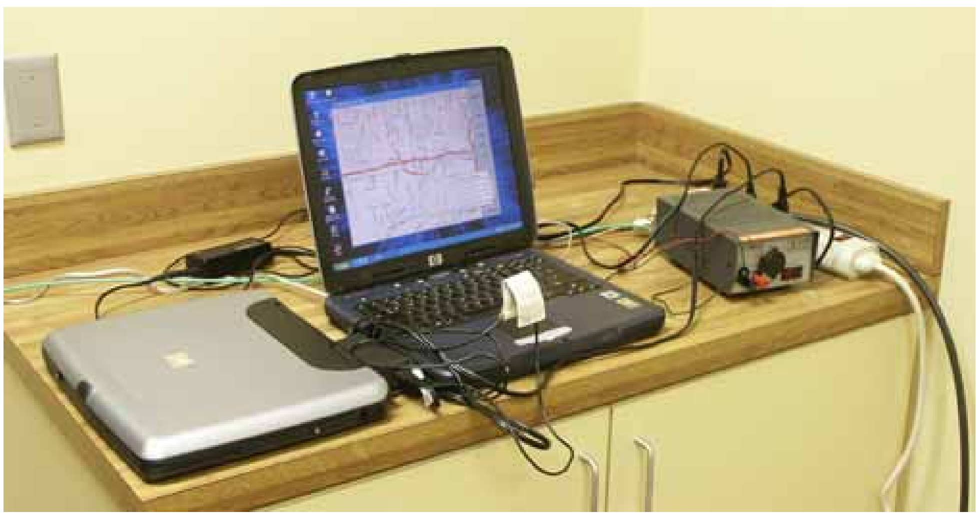


Figure 1. Central System Controller (CSC) for test application.

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.

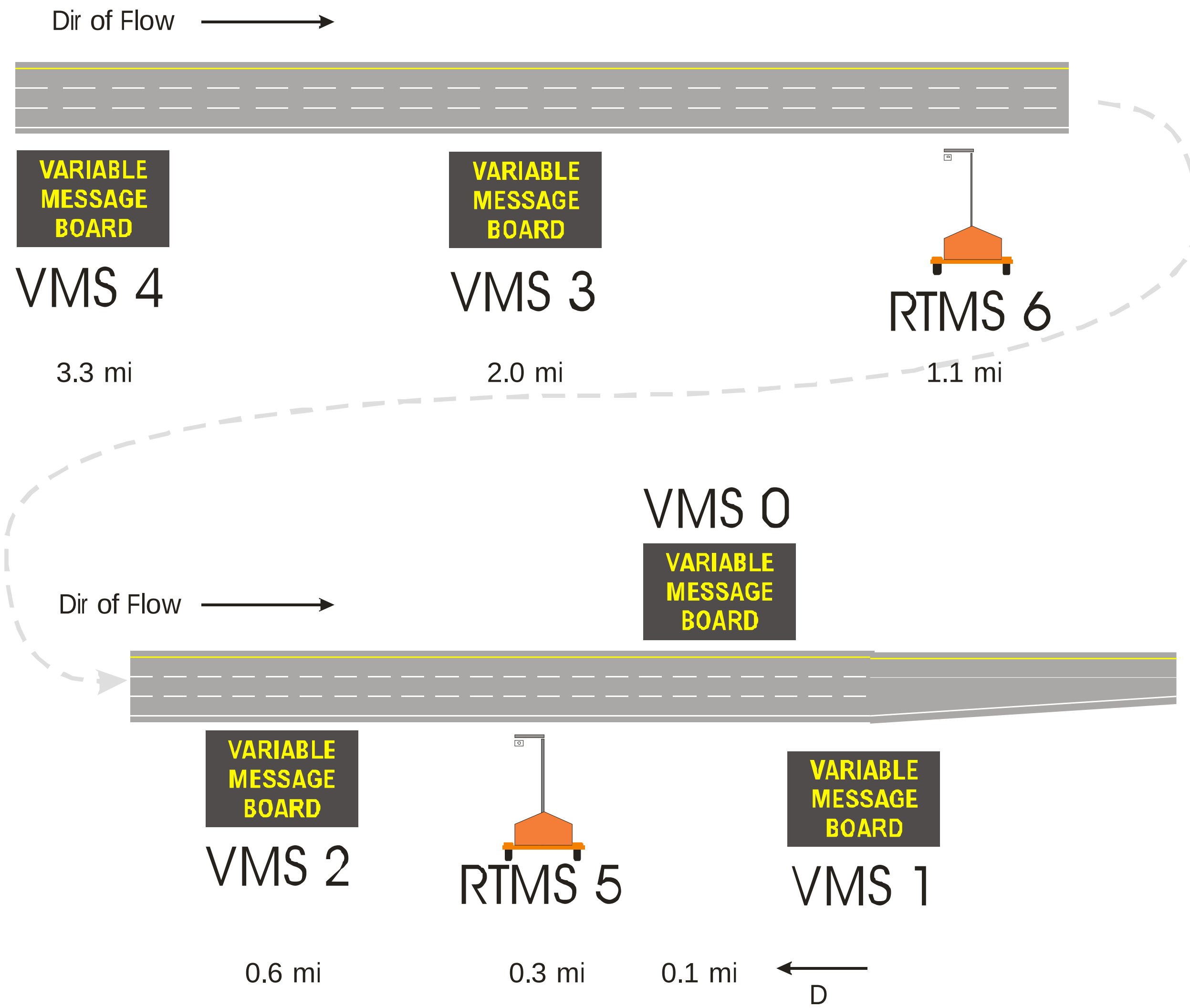


Figure 4. CALM System field components.

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.

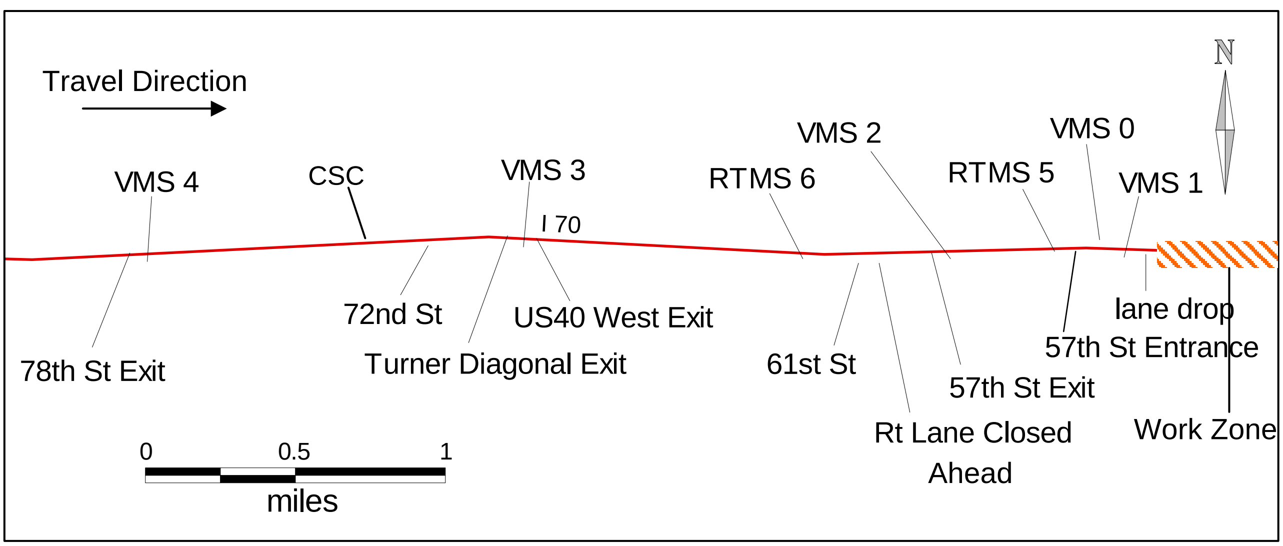


Figure 5. Plan view of study segment.

Figure 6. End of Work Zone Approach

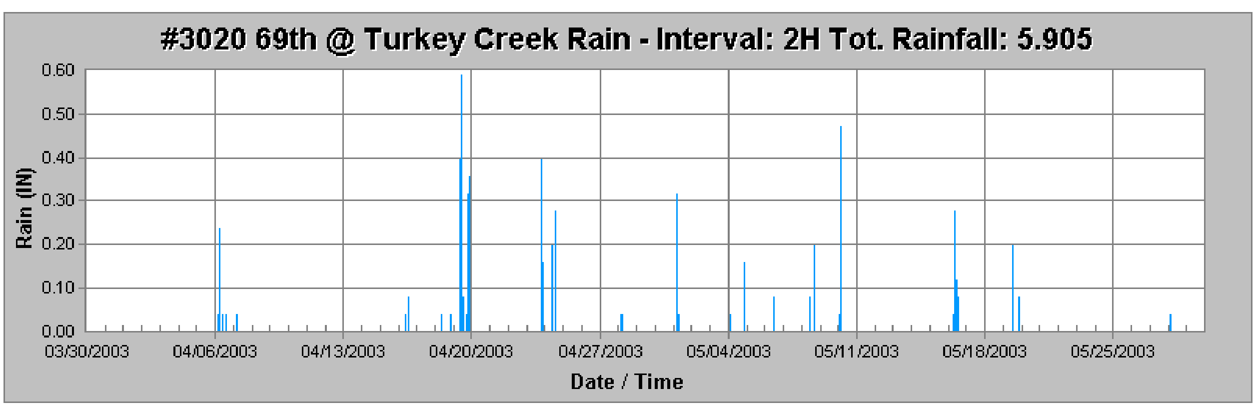
DATA COLLECTION

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.

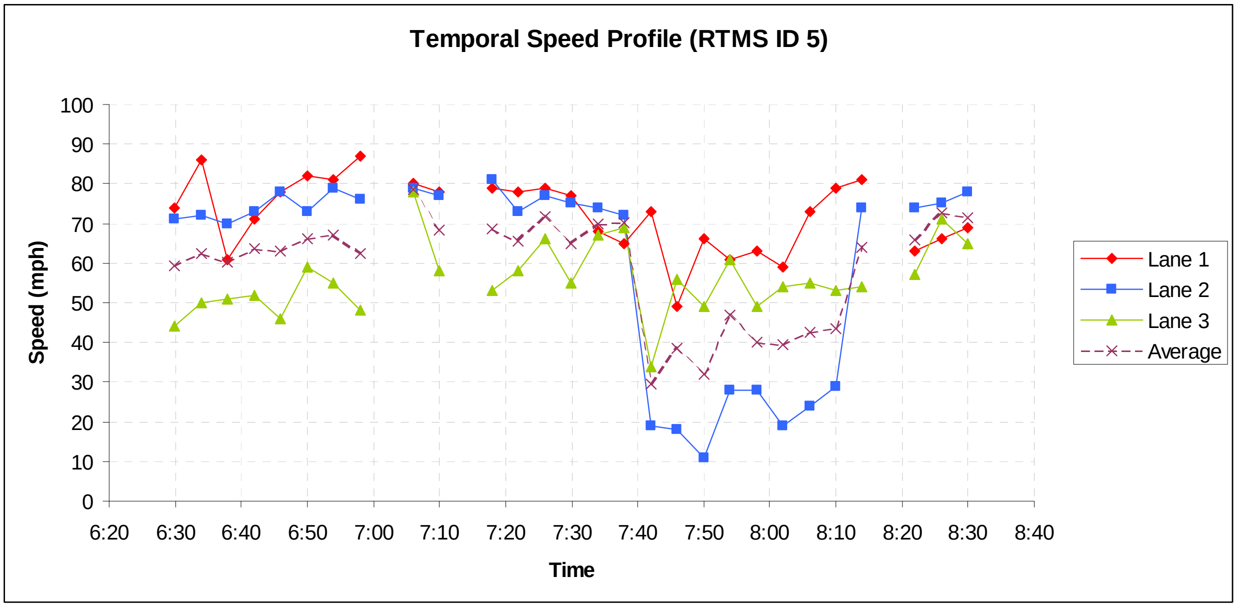


Figure 8. Speed data from RTMS 5 on 4/2/03.

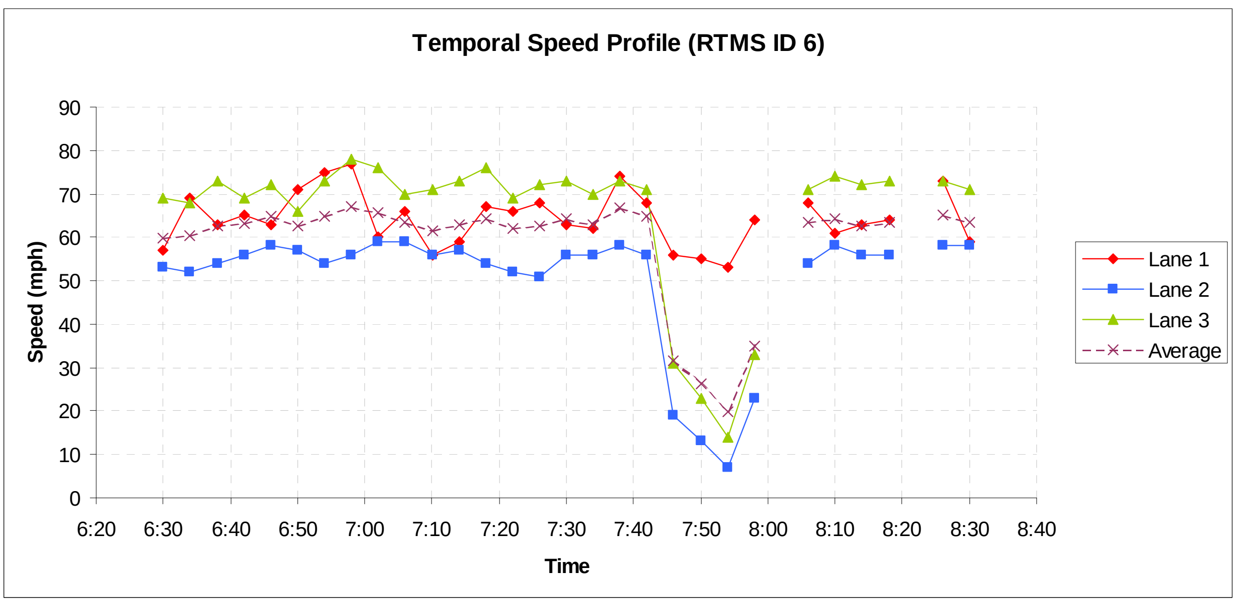


Figure 9. Speed data from RTMS 6 on 4/2/03.

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.