EVALUATION OF TEMPORARY RAMP METERING FOR WORK ZONE SAFETY

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ABSTRACT

Ramp metering has been successfully implemented in many states and studies have documented its positive mobility and safety benefits. However, there have been no studies on the use of ramp metering for work zones. This thesis reports the results from the first deployment of temporary ramp meters in work zones in the United States. Temporary ramp meters were deployed at seven work zones in Missouri. Due to lack of crash data, this study uses video data to extract alternative safety measures such as driver compliance, merging behavior, speed differentials, lane changing, and braking maneuvers.

This evaluation suggests that temporary ramp meters should only be deployed at work zone locations where there is potential for congestion and turned on only during periods of high congestion. In comparison to over 90% compliance rates of permanent ramp meters implemented in other states, field data showed compliance rates from 40.5% to 82.9% in temporary ramp meter. This suggested that non-compliance could be a major safety issue in the deployment of temporary ramp meters. The use of a three-section instead of a traditional two-section signal head used for ramp metering produced significantly higher compliance rates. This thesis then aggregated the data into groups to further analyze the effects of different factors such as platoons, commercial trucks, work zone type and work zone-ramp configuration.

After analyzing general characteristics of mainline and ramp vehicle speed and speed differentials, this study then focused on findings for different comparison groups. The two comparison groups are “between two work zones” versus “before work zone” configuration and “left-lane closed” versus “right-lane closed” work zone type. Results indicated lower mean speeds of mainline and ramp vehicles and higher differentials when

ramp metering was turned on. This is expected and again temporary ramp meters are recommended only where congestion occurs. Congestion will lead to lower mainline speeds thus lower speed differentials either with or without ramp metering. Finally, analysis of merging headways showed that temporary ramp meters were effective in separating platoons before vehicles merged into mainline. This produces more single-vehicle merging which requires shorter gaps and causes fewer impacts on the mainline traffic.

1. INTRODUCTION AND MOTIVATION

Ramp metering has been implemented in the United States since the 1960s (*1*) with the main goal of improving the overall efficiency of a highway system by regulating the traffic entering the mainline. It has been implemented in states such as California, Minnesota, Texas and Florida *(4)* and shown to produce operational benefits in terms of shorter travel times and lower delays.

Despite their documented efficiency and safety benefits, ramp metering strategies have not been explored for work zones. There are no published studies that report on the use of ramp metering in work zones. On the other hand, temporary ramp metering can be suitable for work zone operations due to mainly two facts. First, it is portable, easy to deploy and agencies do not need to have a long-term maintenance plan as they would for permanent ramp metering. Second, work zone reduces capacity thus causing bottlenecks. By using ramp metering on the on-ramps, it should limit the ramp flow and reduce delay and travel times. This study presents the results of temporary ramp metering deployment for work zones.

The study adds to the existing ramp metering and work zone traffic control knowledge in three main ways. First and foremost, this study presents the results from the first deployment of temporary ramp meters in work zones in the United States. Second, this report discusses safety, effects and compliance of temporary ramp metering. Third, unlike previous safety studies, the current study analyzes microscopic safety performance measures since long term crash data is not available. This study informs state transportation agencies about the potential benefits and drawbacks of temporary ramp metering in work zones.

This thesis starts with literature review which focuses on safety aspect of ramp metering studies. Two main types of literatures are transportation agency reports consisting real world crash data and crash prediction modeling with simulation data. Due to the uniqueness of this study, field work is needed to obtain enough data for analyzing alternative safety measures. Next chapter of the thesis consists all the field work information including ramp metering configuration, work zone characteristics, on-site pictures and illustrations. The following chapter describes the methodology used in extraction and analysis of the field data. All the results are in the fifth chapter and they are analyzed follows the order of the methodology chapter. Finally, the thesis concludes all the major findings as well as recommendations for implementing temporary ramp meters and future research trends.

2. LITERATURE REVIEW

Ramp metering has been implemented since 1960s in the United States. It is mainly developed to increase the overall efficiency of a highway system by restricting the entering traffic from the ramp. Algorithms in ramp metering can be divided into two main types: coordinated and un-coordinated. There are also two types of strategies in ramp metering: signal-cycle and one-car-per-cycle (OCPC). OCPC is developed to eliminate traffic platoons when releasing the traffic onto the freeway. In this study, a fixed signal is paired with OCPC strategy to release the traffic at a constant rate and reduce platoons.

Florida Department of Transportation (*2*) activated the ramp metering system on February 4, 2009 for the first time and included a whole crew to operate it. In terms of compliance rate, FDOT worked with Florida Highway Patrol to enforce the ramp signal during the first few weeks of launching. The coverage rate of all ramp metering sites was reduced gradually over time assuming drivers are becoming used to the signal. The whole enforcement period was set to be 13 weeks. Public education period should be a few weeks earlier and ensure as large coverage as possible.

In a ramp meter evaluation report of UDOT (*3*) suggested that ramp metering had the potential in increasing safety of the highway system. They did not actually evaluate it. Instead, they suggested using density as an exposure.

In 2000, Cambridge Systematics did a complete evaluation of selected ramp meters in Twin cities, Minnesota. This study collected data during a five-week period from the end September to December 8th, consisting of two weeks of "with" ramp meter scenario and two weeks of "without" scenario. The additional week was counted as a transition period for the public to adjust to the shut-down of ramp meters. This research proved the efficiency of ramp meters in increasing speed and flow rate on the mainline while reducing travel time for long distance travels on the freeway. It should be noted that this study found 26 percent increase in crashes after ramp meters were deactivated.

In the following report in 2002, another evaluation was conducted for the study period from January to July, 2001. They reported an 15 percent increase in total number of crashes during peak hours when comparing to historical (1998 to 1999) “ramp metered” data.

Lee (*6*) first attempted to quantify safety of ramp metering in real time as previous studies only analyzes aggregated results in terms of safety such as total number of crashes. They developed a microscopic simulation model in PARAMICS based on field data on I-880. ALINEA algorithm was used for controlling ramp metering rates. The key part in this study is the application of a real-time crash prediction model proposed by the same author in 2002 (*7*). This model consists of three independent variables: coefficient of variation of speed, average speed difference between upstream and downstream and average covariance of volume between upstream and downstream. Crash potential is expressed in expected number of crashes per million vehicle-km over 13months. Since the second variable has the most influence on crash potential, this study only used this variable as input. Their results proved the effectiveness of ramp metering in reducing the risk of crashes. Dhindsa (*8*) followed the research and concluded based on his simulation results that ramp metering improves safety on freeways during congestion and more ramp meters along a freeway can further improve safety.

Abdel-Aty and Gayah (*9*) further analyzed the safety aspects in both coordinated and uncoordinated ramp meters using a PARAMICS based simulation model. The coordinated Zone algorithm and the uncoordinated ALINEA algorithm are tested with traditional traffic-cycle-based releasing strategy and one-car-per-cycle (OCPC) strategy. A crash prediction model proposed by the author was used and overall safety index (OSI) and lane change safety index (LCSI) were the main measures of effectiveness. Results indicated that both algorithms reduced rear-end and lane-change crash risks when ALINEA paired with traffic-cycle strategy performed the best. OCPC strategy performed worse than traffic-cycle strategy either with ALINEA or Zone algorithm under congested situations. However, for ALINEA algorithm, shorter cycle length was preferred and about 1 to 2 vehicles were allowed which ensured the minimum turbulence on the mainline. Temporary ramp metering considered for congested area should be linked with ALINEA algorithm and shorter cycle. In this thesis, OCPC strategy is used to achieve minimal effects on the mainline. A modified Zonal-density-based ramp metering algorithm was applied and evaluated in a recent report (*10*). They reported that it was more effective in reducing overall travel time and average delays but no safety measures were mentioned.

3. DATA COLLECTION

3.1 Ramp Metering Control Plan

The temporary ramp meter hardware used in this study was a portable traffic signal that was battery-powered and could be controlled via a remote control. The remote control feature was important in case the meter needed to be turned off in an emergency, or to set the meter to green to prevent spillback. The three-head signal could be configured as a two-head signal by re-wiring and eliminating the amber head.

According to the MUTCD section on entrance ramp control signals, an engineering study should precede the installation of ramp control signals (*11*). The study involved the collection of preliminary ramp volumes to determine the potential for queue spillback and to design a metering rate, the analysis of site geometrics to determine the optimum meter location, the review of regional traffic demand, and the inspection of work zone projects in the region. Permanent ramp meters that were deployed in the state in Kansas City were also examined and used as a template. Three major references, the MUTCD (*11*), the FHWA handbook (*12*) and the Green Book (*13*), were used in the development of the temporary ramp metering plan. Figure 3.1 is a conceptual diagram, and Figure 3.2 is an example of the plan deployed at a work zone on I-70 in Columbia, Missouri. Both figures show the MUTCD specified sequence of signage: "signal ahead" used in place of "ramp meter ahead"; "one vehicle per green"; and "stop here on red" just below the signal head. The height of the signal was extended between 4.5 and 6 feet from the pavement to the bottom of the signal housing according to the MUTCD. Because the ramp meter was deployed near a work zone, the temporary traffic control sections of the MUTCD also applied. Thus the researchers monitored queues closely in real-time to prevent spillover onto arterial streets. The ramp meters were placed in a location in order to strike a balance between queue storage and acceleration distance to the freeway. The acceleration distances were computed using Green Book standards.

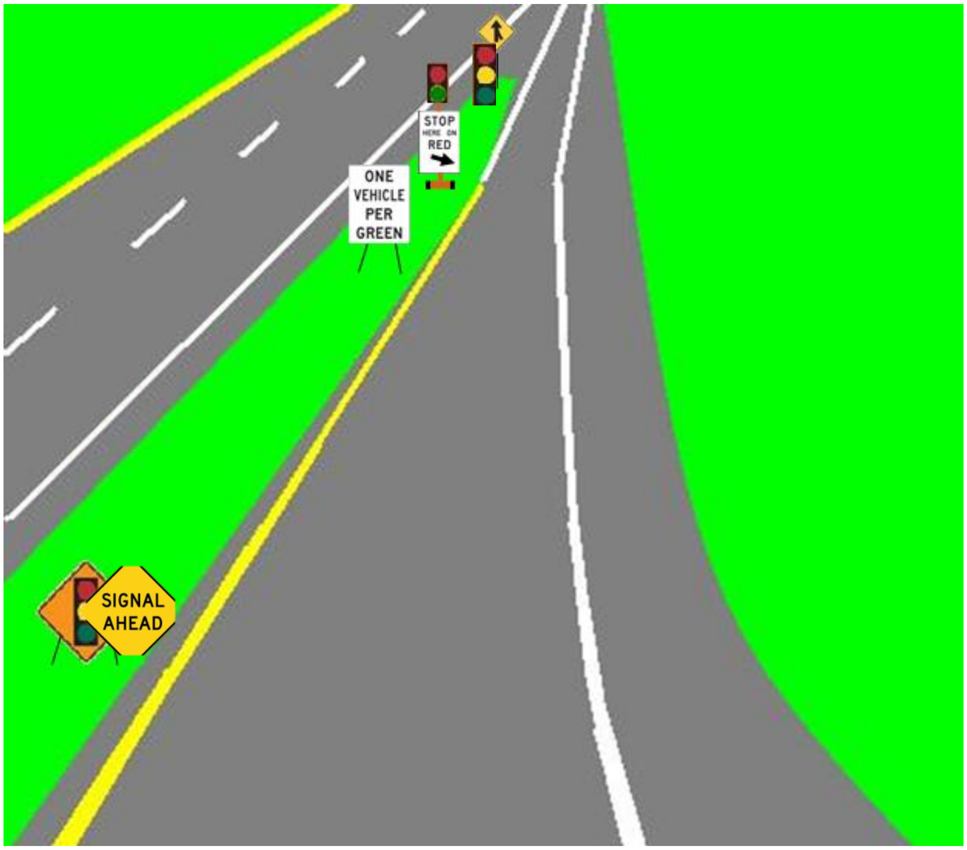

FIGURE 3.1 Conceptual diagram of the temporary ramp meter.

FIGURE 3.2 Ramp metering in operation.

3.2 Field Site Descriptions

Ramp metering was deployed at seven different work zones in Columbia, Missouri, during June and July, 2011. These work zones were deployed near five different ramps as shown in Figure 3.3. These locations were all within the same urban metropolitan area and involved the same driver population. The work zones were located on either Interstate 70 or U.S. Highway 63, both of which are access-controlled high speed facilities. All the work zones involved a two-to-one lane closure. These work zones differed in terms of work zone configuration, location of work zone with respect to the ramp, ramp volume, entrance ramp grade and length, and truck percentage. Table 3.1 shows the characteristics of each work zone. Work Zone 5 had the highest ramp volume as well as an 8% truck volume on the ramp. It was also unique in that the ramp was in between two active work zones. Work zones 1 and 2 preceded the ramp. All other work zones were located after the ramp. All the two-to-one lane closures involved the right lane except for Work Zone 6. Work zones 1, 2, 3, and 5 had downhill ramps, while work zones 4, 6, and 7 had uphill ramps which made acceleration more difficult. The ramp length was measured to the gore point, and Work Zone 3 had a particularly short ramp. The short ramp meant less queue storage; thus it was monitored carefully for spill-back. The distance from the ramp meter to the gore point is shown in the last row.

FIGURE 3.3 Temporary ramp metering field sites (Google maps, 2012).

TABLE 3.1 Work Zone Characteristics

Characteristic	Work Zone						
	1	2	3	4	5	6	7
Facility	I-70	I-70	I-70	I-70	I-70	US-63	US-63
Exit	St. Char.	St. Char.	Prov.	West	US-63	Stad.	Stad.
Date	6/19	6/20	6/27	6/28	7/11	7/12	7/13
Ramp Vol., veh/hour	146	211	137	55	328	222	211
Lane Closed	Right	Right	Right	Right	Right	Left	Right
Ramp Locat.	After	After	Before	Before	Between	Before	Before
Ramp Truck%	0%	0%	0%	0%	8%	2.1%	1%
Grade	-5.7%	-5.7%	-2.4%	1.7%	-0.5%	2.6%	2.6%
Ramp Len., ft	963	963	490	1113	1120	1220	1220
Meter-Gore, ft	471	471	240	632	493	351	351
Taper-Gore, ft	-3913	-3913	6168	800	7085	1687	2181

1. negative number means the taper is upstream of the gore pt.

For each site two figures are presented next: a layout of the work zone and a picture of the ramp meter in operation at the site. The layout illustrates the location of the ramp meter with respect to the gore point as was shown in Table 3.1. The picture shows the grade and the general geometrics of the ramp area. Figures 3.5 and 3.6 show two different signal configurations that were deployed near the mile marker-131 ramp on I-70:

two-head and three-head. Figures 3.9 and Figures 3.10 show the only site with congestion in this study. No speed data is collected for this site. Figures 3.13 and 3.15 show the two different types of lane closure, left and right, on US-63 at Stadium Boulevard.

FIGURE 3.4 Work zone layout, I-70WB @ mile marker 131.

FIGURE 3.5 I-70WB @ mile marker 131, two-head signal.

FIGURE 3.6 I-70WB @ mile marker 131, three-head signal.

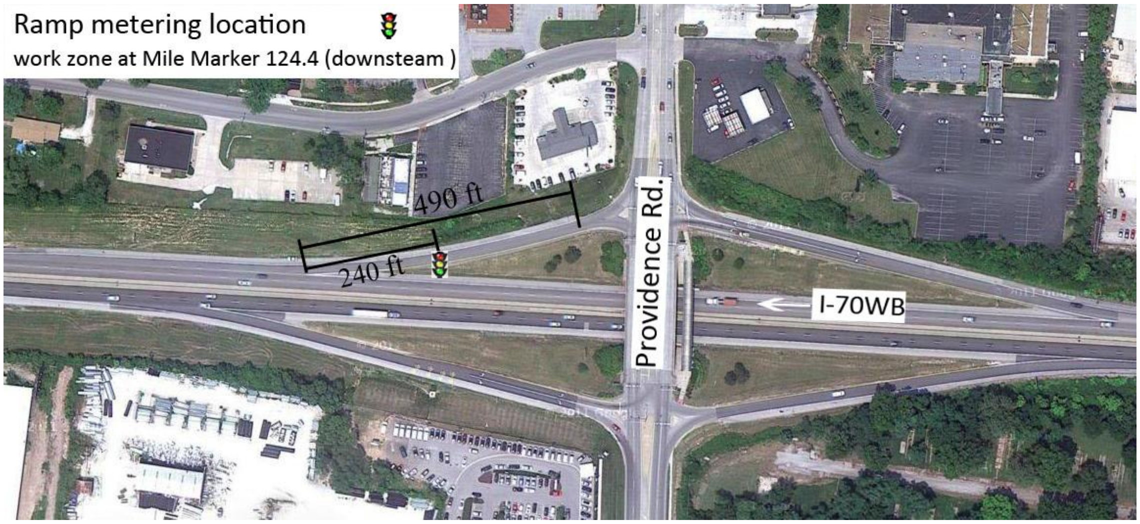

FIGURE 3.7 Work zone layout, I-70WB @ 126.6

FIGURE 3.8 I-70WB @ mile marker 126.6.

FIGURE 3.9 Work zone layout on I-70WB @ mile marker 125.6.

FIGURE 3.10 I-70WB @ mile marker 125.6.

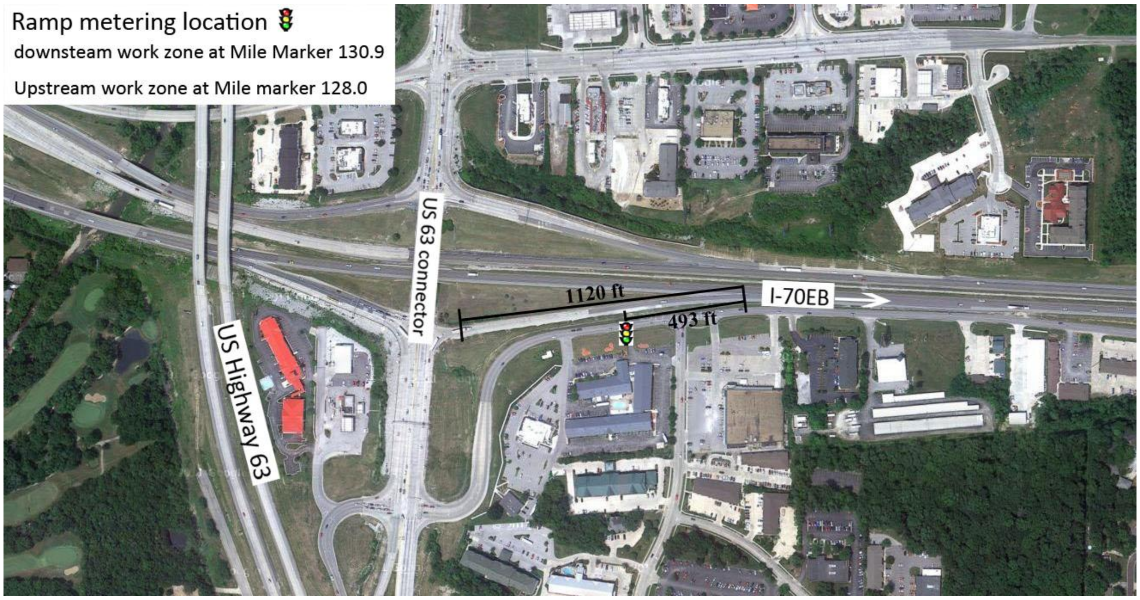

FIGURE 3.11 Work zone layout on I-70EB @ mile marker 129.0.

FIGURE 3.12 Figure I-70EB @ mile marker 129.0.

FIGURE 3.13 Work zone layout on US-63NB @ Stadium, left lane closed.

FIGURE 3.14 US-63NB @ Stadium.

FIGURE 3.15 Work zone layout on US-63 @ Stadium, right lane closed.

4. METHODOLOGY

4.1 Compliance Analysis

Compliance of ramp metering is defined as a vehicle passing the signal on green. If a vehicle passes the signal on red, then it is considered not to be in compliance. In order to better describe the driving behavior while implementing portable ramp meter due to temporary lane closure, this thesis derives a total of 6 scenarios from compliant/non-compliant classification. Based on braking behavior, compliance is further divided into three cases: fully stop, rolling stop and no intent to stop. Similarly, non-compliance also contains three similar categories

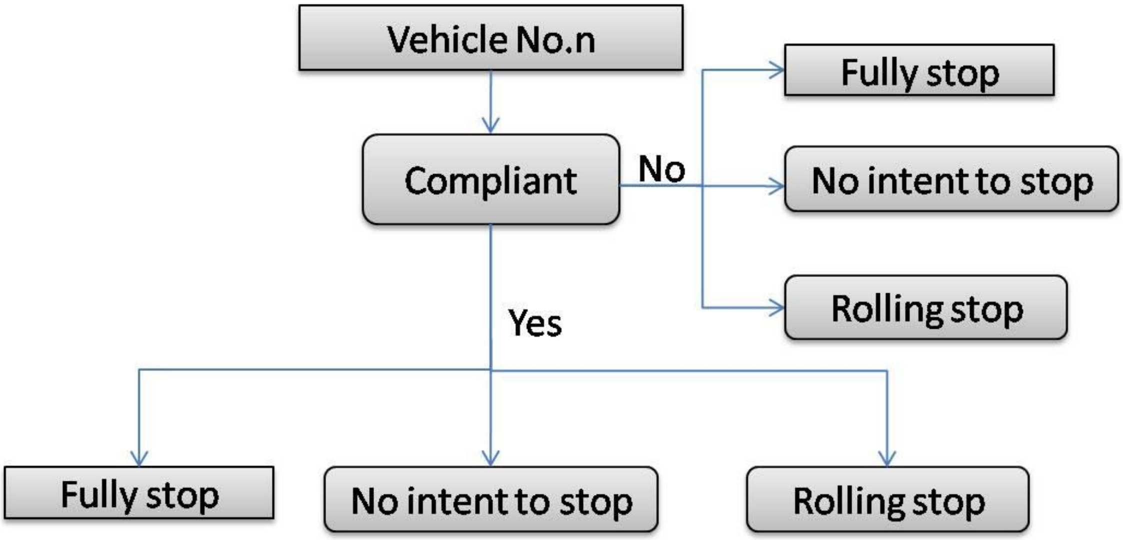

FIGURE 4.1 Compliance classification

TABLE 4.1 Compliance Classification

Compliant	Full stop	Vehicle slows down to a complete stop and starts on green
	Rolling stop	Vehicle slows down without a full stop and accelerates on green
	No intent to stop	Vehicle does not slow down but passes the signal on green
Non-compliant	Full stop:	Vehicle slows down to a complete stop but starts on red
	Rolling stop	Vehicle slows down without a full stop and run the red
	No intent to stop	Vehicle does not slow down and passes signal on red

When processing the data, vehicle type is also recorded. Another variable, called “platoon”, describes those vehicles that are in the queue and their behavior might be affected by the vehicle in front of them. The leader of a platoon is considered as driving in free flow.

The FHWA Ramp Management and Control Handbook (*12*) recommends a minimum cycle time of 4 seconds, composed of 2.5 seconds of red plus 1.5 seconds of green. This results in a discharge rate of 900 vehicles/hour. The lowest practical discharge rate is 240 vehicles/hour from a 15-second cycle time. The MUTCD section on the design of freeway entrance ramp control signals (*11*) allows the use of both two-section and three-section heads, thus both configurations were investigated. After some preliminary calculations of the required discharge rate based on observed ramp flows, the following four signalization schemes were developed:

- 2-section head: 4 seconds red, 2 seconds green, 6 seconds cycle (4R-2G)
- 2-section head: 4 seconds red, 3 seconds green, 7 seconds cycle (4R-3G)
- 3-section head: 4 seconds red, 1 second amber, 3 seconds green, 8 seconds cycle (4R-1Y-3G)

- 3-section head: 4 seconds red, 1 second amber, 2 seconds green, 7 seconds cycle (4R-1Y-2G)

Assuming that only one vehicle is released per cycle, the discharge rates ranged from 450 vehicles/hour to 600 vehicles/hour. All four configurations were deployed on the same ramp at I-70 and St. Charles Road.

4.2 Safety Analysis

Relevant statistical tests were used to assess the validity of results. In terms of safety, since temporary ramp meters are deployed for a short period of time, an adequate sample size of crash data could not be collected. Thus, surrogate measures for safety were employed. These measures include driver compliance rates, speed statistics of the mainline and ramp traffic, speed differences between merging vehicles and mainline vehicles, ramp platoons, merging headways, lane changes and braking events. There was only limited access to congested field sites, because the Missouri Department of Transportation (MoDOT) shifted to night work at congested locations. Despite the fact that all work zones were located in an urban area within metropolitan Columbia, work zones were delayed until after the evening peak had subsided.

A total of four cameras were deployed at each work zone along with two speed radars. A camera on a twenty-foot tripod captured the entire ramp location including both the mainline and the ramp. This was a zoomed-out field-of-view. A zoomed-in field-of-view was recorded in order to have a clearer view of the merging interactions. Figure 4.2 shows the view of the zoomed-out camera with an inserted picture from the zoomed-in camera.

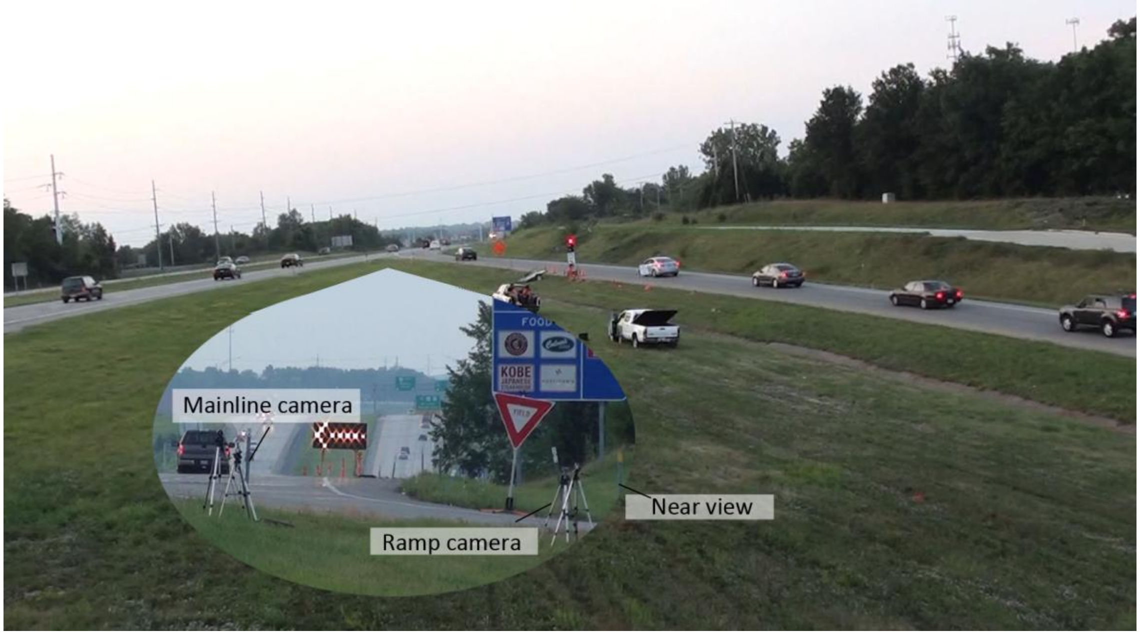

FIGURE 4.2 Radar gun and camera set up.

A camera was paired with a speed radar gun for monitoring the mainline and the ramp as shown in Figure 4.3. Those familiar with radar operation know that radars need to be deployed with skill as unintended vehicles could be picked up such as opposing vehicles. All the cameras were time-synchronized to one another.

(a) (b)

FIGURE 4.3 (a) Mainline camera vision (b) Ramp camera vision.

For compliance analysis, videos of ramp vehicle behavior were captured at each work zone and processed visually with the help of four trained undergraduate research assistants. All data were collected based on the same standards and procedures. Each scenario consisted of 30-minute without ramp metering data and 30-minute with ramp metering data. These two periods were continuous but not in particular order. A vehicle is said to have complied with the ramp meter if it went through the signal when the signal display is green. The vehicle class was recorded so that passenger and commercial vehicles could be studied independently. If more than one vehicle arrived at the meter, the number of platoon vehicles was noted.

Since it was hard to determine the actual merge point for every vehicle, the gore point was used as the common reference point for determining speeds in videos. Three variables were extracted from the mainline video: time when the front end of a vehicle reached the reference line, mainline speed, and vehicle type. Four variables were extracted from the ramp video: time when the front end of a vehicle reached the reference line, speed of the ramp vehicle, vehicle type, and whether the vehicle was in a platoon. Student's t-test was used to test the statistical significance of the difference between mean speeds with and without ramp metering (*14*). Similarly, F-test was used to test the difference in standard deviations (*14*). Both the mainline speeds and ramp speeds were analyzed.

In studying the interactions between a merging vehicle and mainline vehicles, the concept of a platoon-forming threshold was used. This threshold was derived from the Highway Capacity Manual (15) level of service (LOS) criteria for merge and diverge events on freeways. According to HCM, LOS A represents unrestricted merge and diverge conditions. Drivers start to be influenced by merging and diverging maneuvers at LOS B. The critical point between LOS A and B is a density of 10 pc/mi/ln, which is equivalent to 600 pc/hr or an average headway of 6 seconds at the speed of 96.5 kph (60 mph). Therefore, the platoon-forming threshold was set to 6 seconds, meaning that any headway longer than this factor was not relevant to the analysis of merging vehicles. A headway shorter than this factor might result in a merging vehicle causing turbulence on the mainline, resulting in lane-changes or braking maneuvers. The 6-second time headway between the leading and merging vehicle and the merging and trailing vehicle results in a maximum time headway of 12 seconds when leading and trailing were both present. If a platoon was attempting a merge, then this threshold was increased by 6 seconds for each additional vehicle beyond a single merging vehicle. As a sensitivity test, a platoon-forming threshold of 3 seconds is also tested. The results are consistent with 6-second threshold which is shown in the next chapter and there is only a little difference in speed differentials. These results are listed in appendix A.

The speed difference between a merging vehicle and mainline vehicle(s) was extracted for each merging event with and without ramp meter. The relevant mainline vehicle is a vehicle that traveled in the right lane and located either in front or behind the merging vehicle within the platoon-forming factor. After manually extracting individual speeds from video, the mainline vehicles and the merging ramp vehicle were synchronized based on the time they crossed the gore point. The speed differences with and without ramp metering were compared statistically using the aforementioned t-test and the KS distribution test (*14*). The expectation was that vehicles released from ramp meters have a shorter distance to accelerate, resulting in larger speed differences.

Another safety measure extracted from video was headways accepted by merging vehicles. Longer headways on the mainline provide the driver with more time to react and merge safely. For every merge event, the time headway on the mainline was extracted by computing the difference between the time when the leading vehicle or the trailing vehicle crossed the gore point. This time is manually recorded with a stop watch. The gore point was used, since the exact location of the merge was not easily identifiable.

Vehicles merging from an entrance ramp onto the mainline may induce some mainline vehicles to switch from the right lane to the left lane, if open. The number of lane changes that occurred with and without the ramp meter was derived from video. Fewer lane changes indicate less influence by the ramp traffic.

Since accelerating ramp vehicles typically travel slower than mainline vehicles, this may cause mainline vehicles to brake to allow the ramp vehicle to merge. Thus braking events are related to the magnitude of speed differences between merging and mainline vehicles. Such braking events could have a negative impact on safety as they indicate conflicts and rear-end crash potentials. If there were fewer braking events on the mainline with ramp metering, that means ramp metering was effective in reducing potential conflicts during merging events. Braking events were visually extracted from video.

5. RESULTS

5.1 Driver Compliance Rate

Compliance rates are important when deploying ramp metering to ensure safety and efficiency. Table 5.1 shows the general compliance rates by site. Note the first two sites consists of four different signal configurations.

TABLE 5.1. Compliance Rate at Each Location

Date (2011)	location		Compliance rate	
June/19th	I-70WB @Mile marker 131		4R-2G	4R-3G
			40.5%	54%
June/20th	I-70WB @Mile marker 131		4R-1Y-3G	4R-1Y-2G
			69.6%	75.0%
June/27th	I-70WB @Mile marker 126.6	(Providence ramp)	4R-1Y-2G	
			55.9%	
June/28th	I-70WB @Mile marker 125.6	(West Blvd ramp)	4R-1Y-2G	
			67.3%	
July/11th	I-70EB @Mile marker 129	(Hwy 64)	4R-1Y-2G	
			79.0%	
July/12th	Hwy63NB @Stadium Entrance		4R-1Y-2G	
			76.6%	
July/13th	Hwy63NB @Stadium Entrance		4R-1Y-2G	
			82.9%	

A much higher compliance rate resulted when a three-section signal head was used. Field observations of driver behavior supported the statistical disparity between two and three-section head operation. Some drivers simply did not know what to do while facing a temporary two-section head. One possible reason for this disparity could be that drivers were not familiar with permanent ramp meters, but were familiar with the typical three-section signal head. In Missouri, permanent ramp meters with two-section heads have only been deployed in the Kansas City area which is approximately 120 miles away from Columbia. The 4R-1Y-2G scheme had the highest compliance rate. Field observations revealed that 3-second green time was too long, since it sometimes resulted in multiple vehicles released during a single cycle. The statistical significance of the compliance rates among the different signalization schemes was investigated using paired z-tests. According to the comparison results in table 5.2, all comparisons had low p-values, thus were statistically significant except for the comparison between 4R-1Y-2G and 4R-1Y-3G (p-value = 0.20). Because 4R-1Y-2G had the highest statistical compliance rate, it was used for all subsequent deployments. It should be noted that additional green time seems to affect compliance rate but they are not statistically sound. More field data is needed to test the influence of additional-green-time on compliance rate.

TABLE 5.2 Hypothesis test for compliance rates

	p-value
4R-2G vs 4R-3G	0.10
4R-2G vs 4R-1Y-2G	0.00
4R-2G vs 4R-1Y-3G	0.00

4R-3G vs 4R-1Y-2G	0.00
4R-3G vs 4R-1Y-3G	0.03
4R-1Y-2G vs 4R-1Y-3G	0.20

The 4R-1Y-2G signal scheme was deployed at six work zones in total, and the effects of ramp platoons, commercial vehicles and mainline congestion were investigated. Field observations revealed that when there were platoons on the ramps as opposed to individual vehicles, the compliance rate increased. The reason was that once the leading vehicle of a platoon complied with the ramp meter, then all subsequent vehicles also complied. A platoon is defined as two or more vehicles in proximity on a ramp. For analyzing the effect of platoons, data from Work Zones 2, 3, 6 and 7 were used. These work zones all had a similar commercial vehicle percentage of 3% or lower and low mainline volumes. As shown in Table 5.3, the average compliance rates were higher when there were ramp platoons. The 22% higher compliance rate was statistically significant (p-value = 0.00).

TABLE 5.3 Compliance comparison of Platoon condition vs. Free Flow condition

Work zone	Compliance rate	Ramp Volume	Compliance rate	Ramp Volume	Compliance rate difference	p-value
	Platoon condition		Free Flow Condition			
WZ 2	85.7%	42	68.6%	70	17.1%	0.01
WZ 3	76.9%	39	46.6%	88	30.3%	0.00
WZ 6	87.5%	48	67.8%	59	19.7%	0.01

WZ 7	91.1%	45	77.3%	66	13.8%	0.02
Average	85.6%	174	63.6%	283	22.0%	0.00

In this study, commercial vehicles were defined as vehicles other than FHWA Classes 1 and 2, which are motorcycles and passenger cars with one or two-axle trailers including light pickups and minivans. Thus, the commercial vehicle category includes buses, single unit trucks, and semi- and full tractor-trailers. A good description of the FHWA vehicle classification scheme along with graphical illustrations can be found in Pickett (*16*). In Table 5.4, Row A presents the compliance rates for passenger cars and commercial vehicles at work zones 5, 6, and 7 that had commercial vehicle traffic on the ramp. The compliance rate for passenger cars was slightly higher (by 3.3%) than the compliance rate for commercial vehicles. The difference, however, was not statistically significant. The unrealized expectation was that the compliance rate would be higher for commercial vehicles, since commercial drivers are better trained and highly regulated. One reason for the counter-intuitive result was that semi-trailers had difficulty accelerating through the ramp metering within the 2-second green interval. Thus the non-compliance of commercial vehicles were different in nature than passenger vehicles.

TABLE 5.4 Commercial Vehicles, Congestion and WZ Type on Compliance

Row	Compliance rate	Ramp Volume	Compliance rate	Ramp Volume	Difference	P-value
	Passenger Car		Commercial Vehicles			
A	79.8%	361	76.5%	17	-3.3%	0.377

	No Commercial Vehicles		With Commercial Vehicles			
B	65.3%	294	79.5%	378	14.2%	0.000
	Congested		Near Free Flow			
C	67.3%	55	73.8%	619	6.5%	0.161
	Left lane closure		Right lane closure			
D	76.6%	107	72.7%	567	-4.0%	0.189

By examining commercial and passenger vehicles separately, the effects of commercial vehicles on other vehicles on the ramp was possibly neglected, i.e. interaction effects. Thus the data was divided into ramps that had no commercial vehicles and ramps that had commercial vehicle traffic. Row B from Table 4.3 shows the data from Work Zones 2, 3 and 4 where there were no commercial ramp vehicles and from Work Zones 4, 6 and 7 where there were commercial ramp vehicles. This data shows the compliance rate was higher by 14.2% when there were commercial vehicles on ramps. The result was statistically significant at a p-value of 0.000.

Row C from Table 5.4 shows the influence of mainline congestion on ramp compliance. Work Zone 4 was highly congested as mainline speeds slowed to under 30 mph and the level of service was F. Work Zones 2, 3, 5, 6 and 7 were free flowing. Intuitively, it is unclear why mainline congestion might affect ramp compliance behavior. However, the results in Row C of Table 5.4 show a lower compliance rate of 6.5% when congestion was present. The p-value of 0.161 suggests that the difference in compliance rate is not statistically significant.

When comparing different work zone types, work zones 2, 3, 4, 5 and 7 were combined together to obtain a large sample of left lane closures, and Work Zone 6 was the only one with a right lane closure. The results in Row D indicate slightly higher compliance rate when the left lane is closed though the difference is too small to be statistically significant.

The last investigation of compliance was concerning the effects of work zone-ramp configuration. As shown in Table 5.5, the compliance rate was lowest when the entrance ramp was before a work zone and highest when the ramp was between work zones. Hypothesis test results shown in Table 5.6 further confirm that the -8.5% difference between these lowest and highest compliance rates was statistically significant. The compliance rates between 'before vs after', and 'between vs after' were not statistically different.

TABLE 5.5 WZ-Ramp Configurations on Compliance

Compliance rate	Ramp Volume
Before work zone	
70.5%	400
Between work zones	
79.0%	162
After work zones	
75.0%	112

TABLE 5.6 Hypothesis Testing for Compliance across Configurations

Difference	p-value
Before vs. Between	
-8.5%	0.015
Before vs. After	
-4.5%	0.168
Between vs. After	
4.0%	0.220

In summary the compliance analysis shows that lack of compliance could be a significant issue in the deployment of temporary ramp meters. Compliance is lower under free flow conditions on the ramp (63.6%) which might mean that ramp meters should be turned off under low ramp volumes. Congested mainline conditions resulted in a slightly lower compliance rate, but that result might not be statistically significant. The presence of commercial vehicles on ramps helped to increase compliance rates, thus such presence is not a problem in the deployment of temporary ramp meters. Left lane closure might have a positive effect on compliance though it is not statistically shown. Compliance rate was the highest for locations where the metered ramp is between two work zones and lowest for locations where the metered ramp was upstream of the work zone. But it is unclear if the work zone-ramp configuration results suggest a particular strategy with respect to ramp metering implementation.

The compliance rates observed for temporary ramp metering deployments in the current study were considerably lower than the compliance rates reported at permanent ramp metering sites.. Washington DOT reported compliance rates as high as 98% in Seattle, whereas Arizona DOT reported 90% compliance rates in Phoenix deployments (*4*). The possible reasons for higher compliance rates include, the ramp meters have been in place for a longer period of time, both the Seattle and Phoenix deployments utilize educational programs and increased fines to achieve high compliance rates.

5.2 Detailed compliance categories:

As stated in Chapter 4, drivers' responses to temporary ramp metering are divided into six categories. Figure 5.1 to Figure 5.4 compares drivers' reaction to ramp metering among the four signalization schemes: 4 second red – 2 second green(4R-2G), 4 second red – 3 second green(4R-3G) with the two-head signal at the first work zone; 4 second red – 1 second yellow - 3 second green(4R-1Y-3G) at the second work zone and 4 second red – 1 second yellow - 2 second green(4R-1Y-2G) at the remaining 5 work zones.

When looking at 4R-2G and 4R-3G only, which is from the first work zone, it is obvious that with 4R-3G signal plan, the compliance rate is higher with higher percentage of rolling stop compliant (34% vs. 16%). This indicates that with two-head signal, more green time will increase overall compliance rate and as a tradeoff, cause difficulty for drivers to make proper stop-or-go judgments. However, this result does not apply to three-head signal. As shown in Figure 5.3 and 5.4, the percentage of each category is similar between the two signalization schemes.

In addition, when combining rolling stop compliant and non-compliant, as shown in Table 5.7, rolling stop percentages lower than 50% was observed at all schemes except 4R-3G. Unlike no-intent to stop and full stop, rolling stop is more accidental than other two categories and indicates difficulty in stop-go decisions. Lower percentage of rolling stop is preferred. 4R-3G scenario has the highest number and is least recommended for temporary ramp metering.

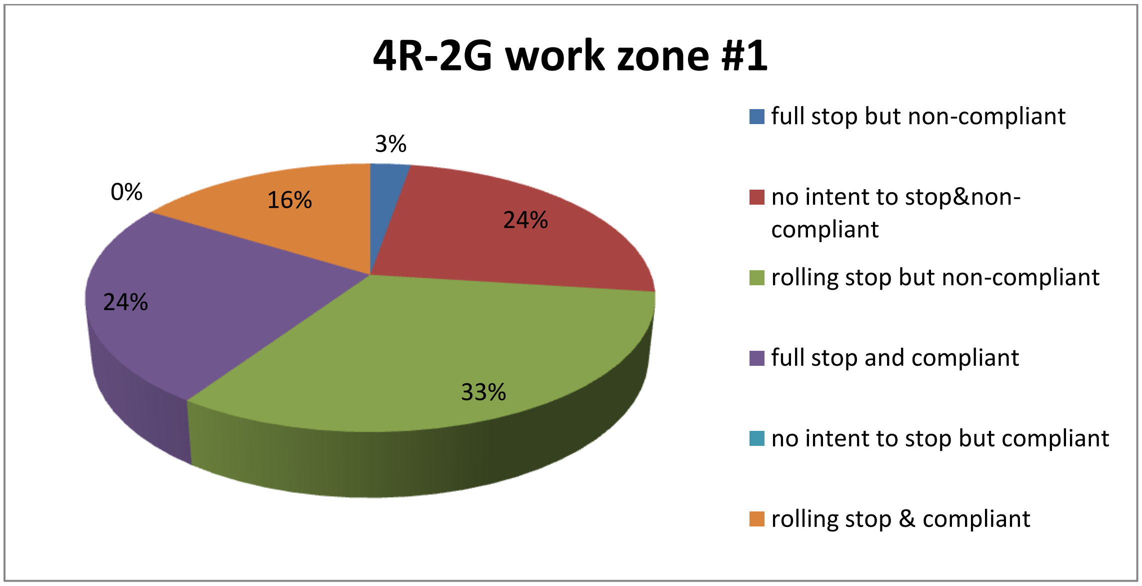

FIGURE 5.1 Compliance related driving behavior during 4R-2G sequence

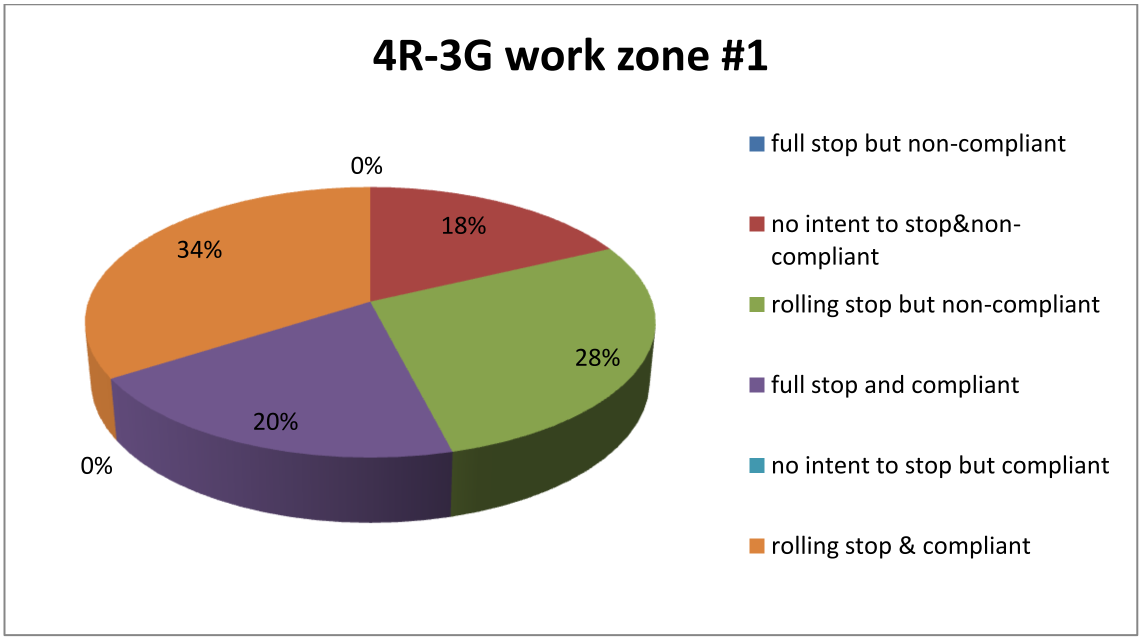

FIGURE 5.2 Compliance related driving behavior during 4R-3G sequence

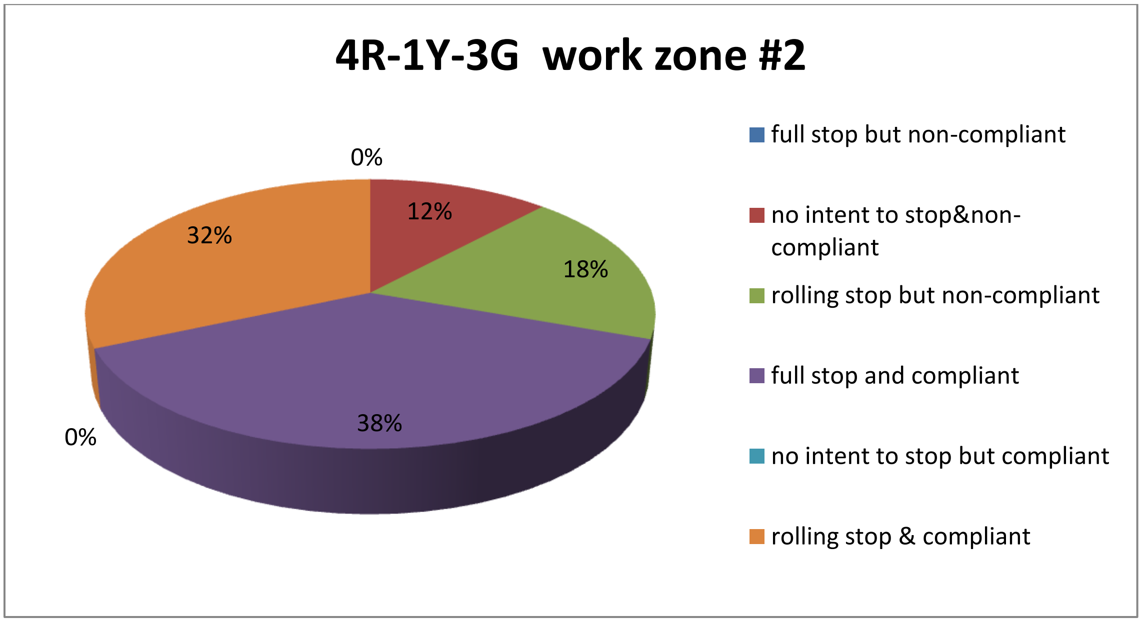

FIGURE 5.3 Compliance related driving behavior during 4R-1Y-3G sequence

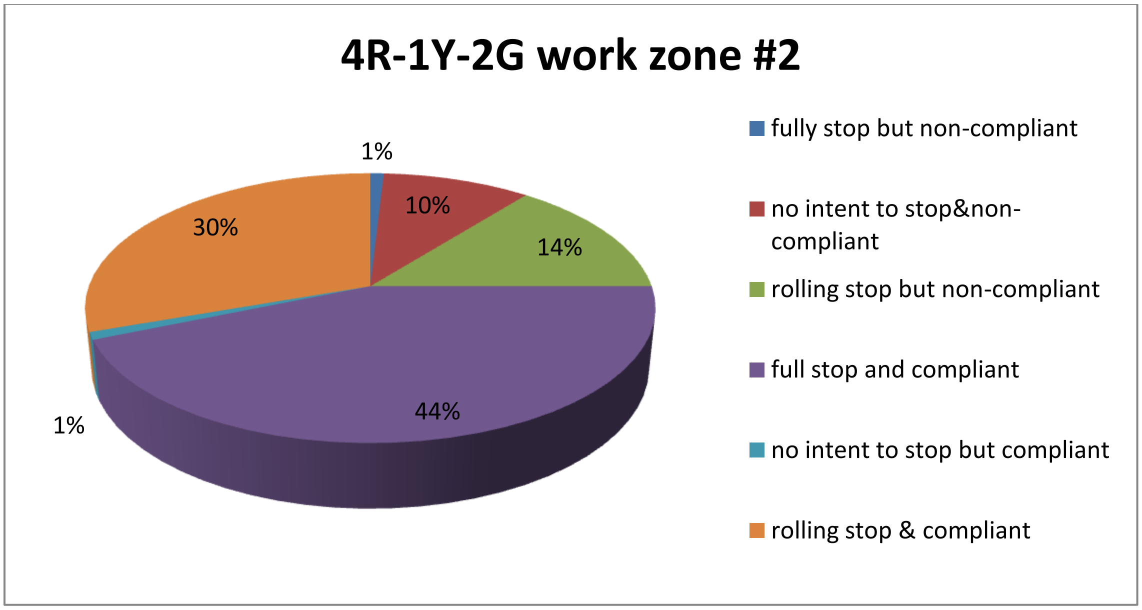

FIGURE 5.4 Compliance related driving behavior during 4R-1Y-2G sequence

TABLE 5.7 Rolling Stop Percentage

Signalization scheme	4R-2G	4R-3G	4R-1Y-3G	4R-1Y-2G
Percentage of Rolling stops	49%	62%	50%	44%

With the same signal scheme, the remaining 5 work zones have similar pie charts. When ramp volume rises and platoon occurs, the percentage of full stop and compliant drivers increase significantly for work zone 5, 6 and 7. Data from other sites is available in appendix B.

5.3 Effect of Temporary Ramp Meter on Speed

5.3.1 Overall Trend Analysis:

Two sets of speed-based performance measures were used to assess the performance of temporary ramp meters. One set of measures included the mean, median and standard deviation of the mainline and the ramp vehicle speeds. Another is the speed differential between a merging vehicle and mainline vehicles that are close to the merging vehicle. Four out of seven work zones produced usable vehicle speeds on both the mainline and the ramp. Some of the work zones had geometric configurations such as horizontal and vertical curves that caused problems for the radar guns. The four work zones shared many similar characteristics such as a two-to-one lane drop, 60 mph speed limit, the similar driver population, the same time-of-day and similar flow rates. Thus the data from these work zones were combined together. At each work zone, speeds were collected for both with and without ramp meter conditions for 30 minutes each. Table 5.8 shows the summary of the speed-related performance measures. For the mainline, the mean speed decreased slightly by 2.58% with ramp operation, but the standard deviation greatly increased by 29%. For ramp speeds, the mean speed decreased by 19.5% with ramp operation, and the standard deviation decreased by 11.6%. It appears that the decrease in ramp speeds caused an increase in the standard deviation in mainline speeds. The changes in mean speed and standard deviation of speed for both mainline and ramp were statistically significant as shown by the p-values for the t- and F-tests.

TABLE 5.8 Speed Measures for Mainline and Ramp

	Sample Size	Mean, mph	Std. Dev., mph	Means, p-value	Variance, p-value
Mainline Speed at Merge Point					
Ramp Meter Off	293	57.26	6.25	0.01	0.00
Ramp Meter On	356	55.78	8.09		
Ramp Speed at Merge Point					
Ramp Meter Off	385	46.88	5.95	0.00	0.07
Ramp Meter On	409	37.74	5.26		
Speed Differentials					
	Sample Size Lead/Follow	Lead, Mean, mph	Follow, Mean, mph	Lead Means, p-value	Follow Means, p-value

Ramp Meter Off	164/153	-10.34	-9.78	0.00	0.00
Ramp Meter On	185/149	-19.39	-19.43		

In addition to aggregate measures such as mean speed and standard deviation, the microscopic measure of the speed differential between a merging ramp vehicle and the mainline vehicle(s) in its vicinity was also analyzed. The speed differential between a merging vehicle and the leading vehicle on the mainline and the speed differential between a merging vehicle and the trailing vehicle on the mainline are shown in Table 5.8. Both speed differentials were significantly higher when the ramp meter was on. Leading speed differences increased by 87.52% and trailing speed differentials increased by 98.67%. These increases were statistically significant. Increases in speed differentials result in a decrease in safety. This could be a result of the existing ramp length and acceleration lane length at the study sites. Longer ramp and acceleration lane lengths will produce smaller speed differentials since ramp vehicles will have longer distances to reach highway speeds.

5.3.2 Speed Data by Sites

As stated before, work zone 3, 5, 6, 7 are used to collect speed related data. Table 5.9 shows the results of t-test on the mean (unequal variance), F-test on the variance and z-test on the truck percentage. Truck percentage is calculated for the right lane only, because left lane is not heavily affected by merging maneuvers. Work zone 5 has the highest truck percentage on the mainline while work zone 6 has the lowest one. Work zone 5 also has the highest truck volume on the ramp due to close to I-70/US63 interchange. All four scenarios show significant differences in speed variance. The median values of speeds before and after ramp deployment remained nearly unchanged. It was interesting to see a difference in mean speed between work zone 6 and 7 because these two work zones were at the same location with similar volume. The only difference was lane closure. Work zone 6 with left lane closed had a mean speed of around 54 mph while the mean speed of work zone 7 was around 58 mph. It might be because of the left lane closure, vehicles were forced to stay on the right lane which was directly affected by the ramp vehicles.

Table 5.10 shows ramp vehicle speeds during merge events. Work zone 5 had the highest mean speed among the four work zones because it had the longest downgrade ramp which allowed plenty room to accelerate. There was at least 8 mph drop in mean speed on the ramp when ramp meter was turned on. This also contributed to the high speed differentials with ramp metering shown in Table 5.11, because mainline mean speed remained the same with ramp metering. Speed differential should be minimized to maximize safety. In order to achieve lower speed differentials, one would have to lower the mainline speed. Thus temporary ramp metering is optimum for congested areas with low mainline mean speeds.

TABLE 5.9 Mainline Vehicle Speed During Merging

Work zone 5	mean	median	Standard deviation	Trucks %
Ramp meter off	59.52	59	4.40	32.16%

Ramp meter on	57.66	59	6.68	37.58%
Work zone 3	mean	median	Standard deviation	Trucks %
Ramp meter off	56.42	57	6.79	11.89%
Ramp meter on	55.12	56	8.54	9.64%
Work zone 6	mean	median	Standard deviation	Trucks %
Ramp meter off	54.77	55	5.31	5.52%
Ramp meter on	53.98	55	9.63	2.94%
Work zone 7	mean	median	Standard deviation	Trucks %
Ramp meter off	58.61	59	6.51	22.30%
Ramp meter on	57.17	58	6.50	21.67%

*Note: all hypothesis tests are performed as one tail at 95% confidence level.

TABLE 5.10 Ramp Vehicle Speed During Merging

Work zone 5		Total count	mean	median	Standard deviation	Trucks %
Ramp meter off		144	50.7	51	5.22	5.56%
Ramp meter on		160	40.3	40.5	4.93	8.13%
Significance test	p-value	N\A	0.00	N\A	0.481	0.186

Work zone 3		Total count	mean	median	Standard deviation	Trucks %
Ramp meter off		241	44.57	45	5.11	2.08%
Ramp meter on		248	36.10	36	5.27	1.62%
Significance test	p-value	N\A	0.00	N\A	0.235	0.353

Work zone 6		Total count	mean	median	Standard deviation	Trucks %
Ramp meter off		97	44.81	44	4.38	3.09%
Ramp meter on		95	36.19	36.5	4.61	2.11%
Significance test	p-value	N\A	0.00	N\A	0.623	0.334

Work zone 7		Total count	mean	median	Standard deviation	Trucks %
Ramp meter off		288	47.57	48	6.25	3.47%
Ramp meter on		313	38.22	39	5.70	4.79%
Significance test	p-value	N\A	0.00	N\A	0.056	0.207

TABLE 5.11 Speed Differential Summary

Work zone 5		**Speed Differential**				
		with leading vehicle		with following vehicle		Both
		Mean (mph)	count	Mean (mph)	count	Mean (mph)
ramp meter off		-8.02	54	-7.77	57	-7.89
ramp meter on		-18.11	74	-19.08	52	-18.51
Significance test	p-value	<0.0001	N\A	<0.0001	N\A	<0.0001
Work zone 3						
		with leading vehicle		with following vehicle		Both
		Mean (mph)	count	Mean (mph)	count	Mean (mph)
ramp meter off		-11.47	111	-10.98	97	-11.24
ramp meter on		-20.25	111	-19.62	97	-19.96
Significance test	p-value	<0.0001	N\A	<0.0001	N\A	<0.0001
Work zone 6						

		with leading vehicle		with following vehicle		Both
		Mean (mph)	count	Mean (mph)	count	Mean (mph)
ramp meter off		-9.91	65	-9.03	58	-9.50
ramp meter on		-18.40	62	-18.25	59	-18.32
Significance test	p-value	<0.0001	N\A	<0.0001	N\A	<0.0001
Work zone 7						
		with leading vehicle		with following vehicle		Both
		Mean (mph)	count	Mean (mph)	count	Mean (mph)
ramp meter off		-10.62	99	-10.24	95	-10.43
ramp meter on		-19.89	123	-20.2	90	-20.02
Significance test	p-value	<0.0001	N\A	<0.0001	N\A	<0.0001

Note: Two tail hypothesis tests are performed at 99% confidence level

5.3.3 Analysis for Different Classification Groups:

The data collected at all sites were classified in two different ways in order to gain insights into the effect of work zone-ramp configuration and left versus right lane closure. One way, “WZ-Ramp configuration”, was to group data based on ramp location in relation to the work zone. Group 1 consisted of sites with entrance ramp before (i.e., upstream) the work zone, and Group 2 consisted of sites with entrance ramp in between two work zones. The second way, “Lane Closure”, involved separating data based on the position of lane closure. Group 1 consisted of sites with a right lane closure, and Group 2 consisted of sites with a left lane closure.

5.3.3.1 WZ-Ramp configuration: Effect of ramp metering on mainline speed

Speed measures for mainline vehicles for the two groups in WZ-Ramp configuration are shown in Table 5.12. For both groups in WZ-Ramp configuration:, mean speed decreased and standard deviation increased when ramp meter was turned on. The small p-values indicate that the changes were statistically significant. The results of the comparison between the two groups in WZ-Ramp configuration with ramp metering are shown in Table 5.13 and without metering in Table 5.14. For both conditions, meter on and off, the mean speed for 'ramp between work zones' group was slightly greater than the mean speed for 'ramp before work zone' group. Thus, in the 'ramp between work zones' group, vehicles on the mainline appeared to have accelerated after leaving the first work zone and thus reached higher speeds than mainline vehicles in the 'ramp before work zone' group. The difference in the mean speeds between the two groups was 2.54 mph with meter and 3.10 mph without meter. The standard deviation of speeds was observed to be higher for the 'ramp before work zone' group. All observed differences were statistically significant.

TABLE 5.12 Mainline speeds during merging

Ramp between work zones	Flow Rate (veh/hr/lane)	Mean	Median	Standard deviation	Trucks %
Ramp meter off	338	59.52	59	4.40	32.16%
Ramp meter on	314	57.66	59	6.68	37.58%

difference	-	1.86	0	-2.28	5.42%
on vs. off, p-value	-	0.015	-	0.00	0.140

Ramp before work zone	Flow Rate (veh/hr/lane)	Mean	Median	Standard deviation	Trucks %
Ramp meter off	391	56.42	57	6.79	11.89%
Ramp meter on	402	55.12	56	8.54	9.64%
difference	-	1.3	1	-1.75	2.25%
on vs. off, p-value	-	0.03	-	0.00	0.091

TABLE 5.13 Comparing mainline speeds with metering for WZ-Ramp configuration

Mainline speed	Sample size	Mean	Standard deviation
Ramp between work zones	93	57.66	6.68
Ramp before work zone	263	55.12	8.54
difference	-	2.54	-1.86
p-value	-	0.002	0.003

TABLE 5.14 Comparing mainline speeds without metering for WZ-Ramp configuration

Mainline speed	Sample size	Mean	Standard deviation
Ramp between work zones	79	59.52	4.40

Ramp before work zone	214	56.42	6.79
difference	-	3.10	-2.39
p-value	-	0.00	0.00

5.3.3.2 WZ-Ramp configuration: Effect of ramp metering on ramp speed

For both groups in WZ-Ramp configuration, the mean speed of ramp vehicles decreased when ramp meter was in operation (Table 5.15). Mean speed reductions of 10.34 mph and 8.47 mph were observed for ‘ramp between work zones’ and ‘ramp before work zone’ groups, respectively. The reduction in speeds was also evident in the speed distribution plots. Figure 5.5 illustrates approximately 20mph shift in speed distribution when the ramp meter was on. The differences in standard deviation of speeds with and without meter were not statistically significant for either group. The ramp speeds for each group were compared using Tables 5.16 and 5.17 for with and without ramp metering conditions. Similar to the mainline speed findings, the mean speed of ramp vehicles was higher for the ‘ramp between work zones’ group compared to the ‘ramp before work zone’ group for both with meter (4.20 mph) and without meter (6.13 mph) conditions.

TABLE 5.15 Speed of ramp vehicles during merging

Ramp between work zones	Flow Rate (veh/hr/lane)	Mean	Median	Standard deviation	Trucks %
Ramp meter off	292	50.7	51	5.22	5.56%
Ramp meter on	328	40.3	40.5	4.93	8.13%
difference	-	10.34	10.5	0.29	-2.57%

on vs. off, p-value	-	0.00	-	0.481	0.186

Ramp before work zone	Flow Rate (veh/hr/lane)	Mean	Median	Standard deviation	Trucks %
Ramp meter off	174	44.57	45	5.11	2.08%
Ramp meter on	187	36.10	36	5.27	1.62%
difference	-	8.47	9	-0.16	0.46%
on vs. off, p-value	-	0.00	-	0.235	0.353

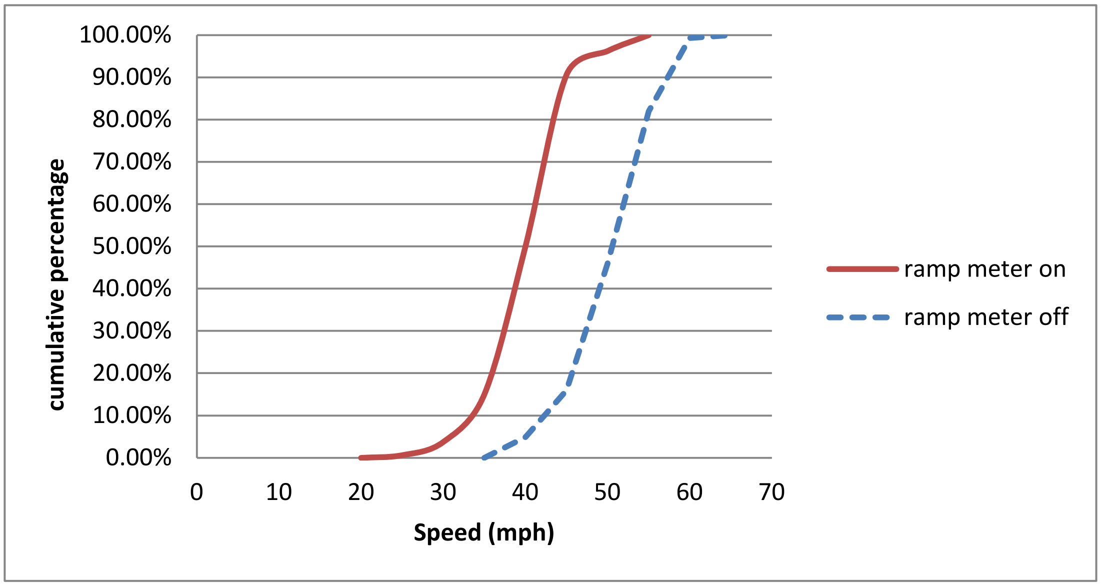

FIGURE 5.5 Cumulative distribution of speeds for the ‘ramp between work zones’ group.

TABLE 5.16 Comparing ramp speeds with metering for WZ-Ramp Configuration

Ramp speed	Sample size	Mean	Standard deviation
Ramp between work zones	160	40.30	4.93
Ramp before work zone	248	36.10	5.27
difference	-	4.20	-0.34
p-value	-	0.00	0.185

TABLE 5.17 Comparing ramp speeds without metering for WZ-Ramp Configuration

Ramp speed	Sample size	Mean	Standard deviation
Ramp between work zones	144	50.7	5.22
Ramp before work zone	241	44.57	5.11
difference	-	6.13	0.11
p-value	-	0.00	0.379

5.3.3.3 WZ-Ramp configuration: Effect of ramp metering on speed differential

During merging events, the difference of speeds between the merging ramp vehicle and its leading and following mainline vehicles were computed. The mean values for both groups are shown in Table 5.18. The mean speed differential increased due to ramp meter deployment in both groups. The increase was greater for the 'ramp between work zones' group (10.09 mph with leading vehicle and 11.31 mph with following vehicle) than the ‘ramp before work zone’ group (8.78 mph with leading vehicle and 8.64 mph with following vehicle).

TABLE 5.18 Speed differentials for WZ-Ramp configuration

	Speed differential				
	with leading vehicle		with following vehicle		Both
	Mean (mph)	count	Mean (mph)	count	Mean (mph)
Ramp between work zones					
ramp meter off	-8.02	54	-7.77	57	-7.89
ramp meter on	-18.11	74	-19.08	52	-18.51
Difference	10.09	-	11.31	-	10.62
p-value	0.00	-	0.00	-	0.00
Ramp before work zones					
ramp meter off	-11.47	111	-10.98	97	-11.24
ramp meter on	-20.25	111	-19.62	97	-19.96
Difference	8.78	-	8.64	-	8.72
p-value	0.00	-	0.00	-	0.00

The mean speed differential values for both groups were compared. The results with meter deployed are shown in Table 5.19 and without meter in Table 5.20. The differences reported for leading vehicle speed differentials, of 2.14 mph with meter and 3.45 mph without meter, were statistically significant. Thus, with ramp metering in place the difference in mean speed differential between ‘ramp between work zones’ and ‘ramp before work zone’ groups was lower than without metering. In addition, when ramp meter is on, the differences of speed differential between the two groups are not statistically significant which means they are very close.

TABLE 5.19 Comparing speed differentials with metering for WZ-Ramp configuration

Ramp metering on	Speed Differential			
	with leading vehicle		with following vehicle	
	Mean (mph)	Sample size	Mean (mph)	Sample size
Ramp between work zones	-18.11	74	-19.08	52
Ramp before work zone	-20.25	111	-19.62	97
Difference	2.14	-	0.53	-
p-value	0.06	-	0.35	-

TABLE 5.20 Comparing speed differentials without metering for WZ-Ramp configuration

Ramp metering off	Speed Differential			
	with leading vehicle		with following vehicle	
	Mean (mph)	Sample Size	Mean (mph)	Sample size
Ramp between work zones	-8.02	54	-7.77	57

Ramp before work zone	-11.47	111	-10.98	97
Difference	3.45	-	3.21	-
p-value	0.00	-	0.00	-

In summary, for both groups in WZ-Ramp configuration, mean speed decreased and standard deviation increased when ramp meter was turned on. When an entrance ramp is located between two work zones, vehicles on the mainline tend to accelerate as they leave the first work zone and arrive at the ramp merge location with speeds slightly higher than those observed at locations where an entrance ramp is before a work zone. However, the standard deviation of the speeds for the ‘ramp between work zones’ group was slightly lower than that of the ‘ramp before work zone’ group. The addition of a ramp meter on the entrance ramp reduced speeds of entering vehicles in both groups, with ‘ramp between work zones’ witnessing a slightly higher drop of 10.34 mph. This was a result of the need to stop at the signal and then to accelerate to the merge point. As expected, the mean speed differential between the ramp vehicle and the mainline vehicle (leading and following) during merging increased due to the deployment of a ramp meter for both groups. The mean speed differential with leading vehicle for the ‘ramp before work zone’ group was 2.14 mph higher than that of the ‘ramp between work zones’ group. Because the differences between the two groups are small, the lower standard deviation in the mainline speeds and the lower speed differential observed in the ‘ramp between work zones’ group might not indicate that ramp meter may be better suited to situations when an entrance ramp is located between two work zones.

5.3.3.4 Lane Closure: Effect of ramp metering on mainline speed

Lane closure involved separating field data based on the position of lane closure: Group 1 being sites with a right lane closure and Group 2 being sites with a left lane closure. Speed measures for mainline vehicles for the two groups in Lane Closure are shown in Table 5.21. The mean speed slightly decreased for the ‘left lane closure’ group

(< 1 mph) and the ‘right lane closure’ group (1.44 mph) upon deploying the ramp meter. The standard deviation increased in ‘left lane closure’ but remained the same in ‘right lane closure’. The results of comparison between the two groups with ramp metering are shown in Table 5.22 and without metering in Table 5.23. For both conditions, meter on and off, the mean speed for ‘left lane closure’ group was lower than the mean speed for ‘right lane closure’ group. The differences in the mean speeds between the two groups were similar with (3.19 mph) or without the ramp meter (3.84 mph) without the meter. The deployment of ramp meter resulted in a higher standard deviation for the ‘left lane closure’ group than the ‘right lane closure’ group.

TABLE 5.21 Mainline speeds during merging for Lane Closure

Left lane closure	Flow Rate (veh/hr/lane)	Mean	Median	Standard deviation	Trucks %
Ramp meter off	344	54.77	55	5.31	5.52%
Ramp meter on	367	53.98	55	9.63	2.94%
difference	-	0.79	0	-4.32	2.58%
on vs. off, p-value	-	0.404	-	0.00	0.060
Right lane closure	Flow Rate (veh/hr/lane)	Mean	Median	Standard deviation	Trucks %
Ramp meter off	387	58.61	59	6.51	22.30%
Ramp meter on	382	57.17	58	6.50	21.67%
difference	-	1.44	1	0.01	0.63%
on vs. off, p-value	-	0.015	-	0.49	0.400

TABLE 5.22 Comparing mainline speeds with metering for Lane Closure

Mainline speed	Sample size	Mean	Standard deviation
Left lane closure	152	53.98	9.63
Right lane closure	202	57.17	6.50
difference	-	-3.19	3.13
p-value	-	0.00	0.00

TABLE 5.23 Comparing mainline speeds without metering for Lane Closure

Mainline speed	Sample size	Mean	Standard deviation
Left lane closure	103	54.77	5.31
Right lane closure	190	58.61	6.51
difference	-	-3.84	-1.20
p-value	-	0.00	0.01

5.3.3.5 Lane Closure: Effect of ramp metering on ramp speed

For both groups in Lane Closure, the mean speed of ramp vehicles decreased when ramp meter was in operation (Table 5.24). Mean speed reductions of 8.62 mph and 9.35 mph were observed for ‘left lane closure’ and ‘right lane closure’ groups, respectively. The differences in standard deviation of speeds with and without meter were not statistically significant for either group. The ramp speeds for each group were compared using Tables 5.25 and 5.26 for with and without ramp metering conditions. The mean speed and standard deviation of ramp vehicles was higher for the 'right lane closure' group compared to the 'left lane closure' group for both with and without metering.

TABLE 5.24 Speed of ramp vehicles during merging for Lane Closure

Left lane closure	Flow Rate (veh/hr/lane)	Mean	Median	Standard deviation	Trucks %
Ramp meter off	218	44.81	44	4.38	3.09%
Ramp meter on	222	36.19	36.5	4.61	2.11%
difference	-	8.62	7.5	-0.23	0.98%
on vs. off, p-value	-	0.00	-	0.623	0.334
Right lane closure	Flow Rate (veh/hr/lane)	Mean	Median	Standard deviation	Trucks %
Ramp meter off	201	47.57	48	6.25	3.47%
Ramp meter on	228	38.22	39	5.70	4.79%
difference	-	9.35	9	0.55	-1.32%
on vs. off, p-value	-	0.00	-	0.056	0.207

TABLE 5.25 Comparing ramp speeds with metering for Lane Closure

Ramp speed	Sample size	Mean	Standard deviation
Left lane closure	95	36.19	4.61
Right lane closure	313	38.22	5.70
difference	-	-2.03	-1.09

p-value	-	0.00	0.01

TABLE 5.26 Comparing ramp speeds without metering for Lane Closure

Ramp speed	Sample size	Mean	Standard deviation
Left lane closure	97	44.81	4.38
Right lane closure	288	47.57	6.25
difference	-	-2.76	-1.87
p-value	-	0.00	0.00

5.3.3.6 Lane Closure: Effect of ramp metering on speed differential

The mean values of speed differentials for both groups are shown in Table 5.27. As expected, the mean speed differential increased due to ramp meter deployment in both groups. The increase was slightly greater for the 'right lane closure' group (9.27 mph with leading vehicle and 9.96 mph with following vehicle) than the 'left lane closure' group (9.22 mph with leading vehicle and 8.49 mph with following vehicle).

The mean speed differential values for both groups were compared. The results with meter deployed are shown in Table 5.28 and without meter in Table 5.29. The values shown in the tables indicate that the differences between the two groups were minor (< 2mph) and not statistically significant.

TABLE 5.27 Speed differentials for Lane Closure

	Speed differential				
	with leading vehicle		with following vehicle		Both
	Mean (mph)	count	Mean (mph)	count	Mean (mph)
Left lane closure					
ramp meter off	-9.91	65	-9.03	58	-9.50
ramp meter on	-18.40	62	-18.25	59	-18.32
Difference	8.49	-	9.22	-	8.82
p-value	0.00	-	0.00	-	0.00
Right lane closure					
ramp meter off	-10.62	99	-10.24	95	-10.43
ramp meter on	-19.89	123	-20.2	90	-20.02
Difference	9.27	-	9.96	-	9.59
p-value	0.00	-	0.00	-	0.00

TABLE 5.28 Comparing speed differentials with metering for Lane Closure

Ramp metering on	Speed Differential			
	with leading vehicle		with following vehicle	
	Mean (mph)	Sample Size	Mean (mph)	Sample size

Left lane closure	-18.40	62	-18.25	59
Right lane closure	-19.89	123	-20.2	90
Difference	1.49	-	1.95	-
p-value	0.16	-	0.10	-

TABLE 5.29 Comparing speed differentials without metering for Lane Closure

Ramp metering off	Speed Differential			
	with leading vehicle		with following vehicle	
	Mean (mph)	Sample size	Mean (mph)	Sample size
Left lane closure	-9.91	65	-9.03	58
Right lane closure	-10.62	99	-10.24	95
Difference	0.71	-	1.21	-
p-value	0.28	-	0.15	-

In summary, the mean speed of mainline vehicles slightly decreased for the ‘left lane closure’ group and the ‘right lane closure’ group upon deploying ramp meter. The standard deviation increased in ‘left lane closure’ but remained the same in ‘right lane closure’ group. The deployment of ramp meter did not have an effect on the difference in the mean speeds between the two groups but resulted in a higher standard deviation for the ‘left lane closure’ group than the ‘right lane closure’ group. The reduction in mean speeds of ramp vehicles with ramp metering was similar for both groups. The mean speed and standard deviation of ramp vehicles was higher for the ‘right lane closure’ group compared to the ‘left lane closure’ group for both with and without metering conditions. Finally, the difference in mean speed differential values between the two groups was found to be insignificant. These findings are not conclusive enough to recommend ramp meter for one group over the other. The lower standard deviation in the mainline speeds and the higher mean speeds of ramp vehicles make the ‘right lane group’ a better candidate for ramp metering. However, the ‘right lane closure’ group also exhibited higher standard deviations in ramp vehicle speeds than the ‘left lane closure’ group.

5.4 Measures Associated with Merge Point

Several additional measures associated with the interaction of the merging ramp vehicle with mainline vehicles were analyzed. These include merging headways, merging platoons, mainline lane changes and mainline braking. The headways accepted by merging vehicles were examined to see if there were any differences between the ‘with’ and ‘without’ ramp meter conditions. In general, a longer headway accepted by a merging vehicle is safer than a shorter headway. A slight shift in the headway distribution towards longer headways was observed due to ramp metering. For example, according to Figure 5.6, the median value of headway was 6.24 seconds with ramp meters as opposed to 5.82 seconds without ramp meters. However, the result of the K-S test comparing the two cumulative distributions was not statistically significant (p-value = 0.417).

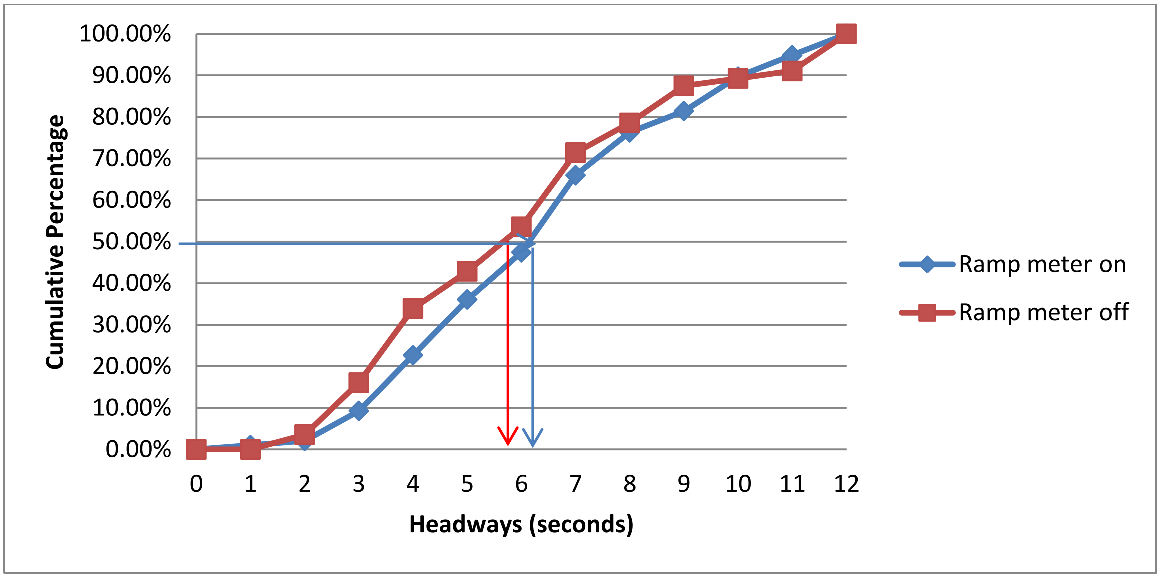

FIGURE 5.6 Merging headway cumulative distribution plot

Two or more vehicles merging simultaneously is defined as a platoon merge in this study. Although there is not enough samples to do comparisons among platoon sizes, there was sufficient data to compare statistically a single-vehicle merging versus multi-vehicle merging. Longer minimum gaps are required for multi-vehicle merging than single-vehicle merging. One objective of ramp meters is to break up platoon merges so that merging could be safer and less disruptive to mainline traffic. Figure 5.7 shows the frequency of platoon merges for different number of vehicles. Of particular interest, is the percentage of single-vehicle merges which was over 70% for metering and less than 50% for without ramp metering. Correspondingly, Figure 5.7 indicates that ramp metering results in fewer platoon merges. This result is desirable from a safety perspective.

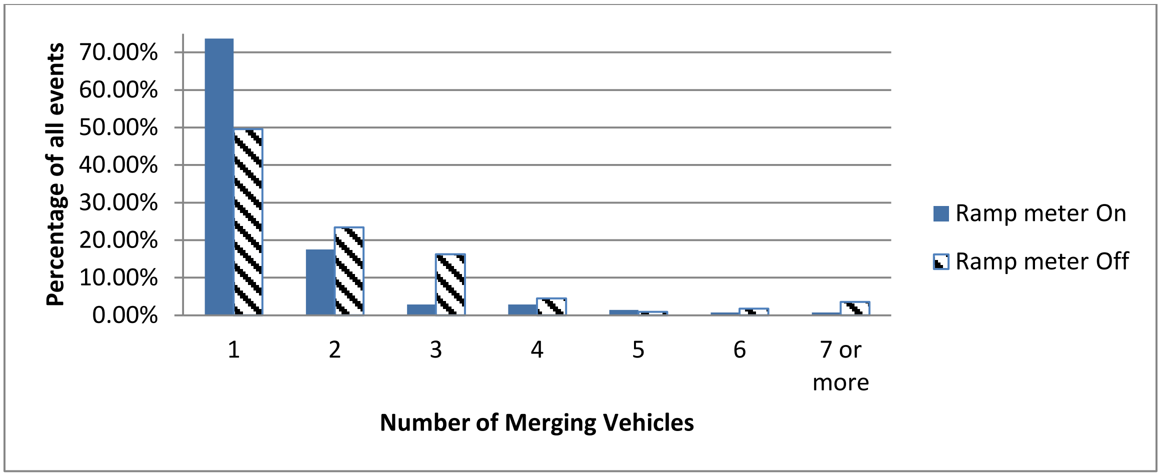

FIGURE 5.7 Frequency of multi-vehicle merges.

5.5 Lane Change events on mainline

There is no lane change under work zone 6 since all vehicles travels in right lane due to left lane closure. It is hard to judge from work zone 3 and 5 whether ramp metering is reducing lane change events or not due to low p-value shown in Table 5.30. However, there is a significant rise in lane change events in work zone 5, from 8.54% to 21.21%. This site also has high truck percentage on the ramp and causing backups during ramp metering operation. Vehicles on the mainline might see the queue and then changed lane to avoid conflicts. More data with high volume ramp traffic and low truck percentage is needed to verify the effect of ramp meter increasing lane change events.

TABLE 5.30 Lane Change Events

	Lane change/total volume		p-value
	ramp meter off	ramp meter on	
Work Zone 5	8.54%	21.21%	0.0004
Work Zone 3	11.48%	9.25%	0.159
Work Zone 7	10.44%	12.82%	0.471

5.6 Braking events on mainline

There are few braking events due to merging across all scenarios. Only two sites, work zone 3 and work zone 6, have large enough sample sizes to perform statistical analysis. However, results shown in Table 5.31 indicate no difference before and after ramp metering operation.

TABLE 5.31 Braking events

Braking	ramp meter off	ramp meter on	p-value
Work Zone 3	8.54%	6.62%	0.092
Work Zone 6	15.86%	13.07%	0.167

6. CONCLUSIONS

This evaluation suggests that temporary ramp meters should only be deployed at locations where there is potential for congestion and turned on only during periods when demand exceeds capacity. The drawbacks outweigh the minor benefits when the ramp meter is used for non-congested conditions. The compliance rate is relatively low (e.g. 63.6%) when there are few vehicles on the ramps. And under such conditions, the objective of breaking up platoons of merging vehicles is not achieved since there are no ramp vehicle platoons. Under non-congested conditions, ramp speeds are reduced significantly (e.g. -19.5%), resulting in increases in both mainline speed variance (e.g. +29%) and speed differential between merging vehicle and mainline vehicle (e.g. +98.67%). Under congested conditions, the mainline speeds are much lower thus such drawbacks do not appear. Even under non-congested conditions, ramp meters beneficially shift the frequency distribution of merging platoons towards smaller platoon sizes.

The compliance analysis showed that lack of compliance could be a major safety issue in the deployment of temporary ramp meters. The lack of compliance could occur due to three possible reasons: 1) the temporary nature of such deployments could catch drivers by surprise, 2) the ramp designs may not be ideal for ramp metering, and 3) the driver population in the study location may not be familiar with freeway ramp metering. These three reasons are not mutually exclusive. The use of a three-section signal head instead of a traditional two-section ramp signal head used produced significantly higher compliance rates. This finding could be attributed to the familiarity of drivers with the three-section signal head at intersections. Thus, the use of a three-section signal head is recommended for temporary ramp meter deployments in work zones, especially at locations where driving population is not familiar with ramp metering.

Data shows no statistically significant difference in mainline speed, ramp speed and speed differential between “ramp between work zones” and “ramp before work zones” groups. Future research could study “ramp within work zones” and compare it with the previous two groups.

The “left-lane closed” work zones have lower mean speeds on both mainline and ramp than “right-lane closed” work zones. The difference is statistically significant and is consistent whether ramp meter is deployed or not. Thus it cannot be determined which type of work zone benefits more from temporary ramp metering.

This study confirms ramp meter’s effectiveness of breaking up ramp platoons. A safe single-vehicle-merging requires shorter ***minimum*** gaps on the mainline than multi-vehicle merging does. Drivers tended to choose longer gaps to merge when ramp meter was turned on. This could be a main benefit of temporary ramp meter it allows drivers more time to react to incidents. However, in order to verify it, larger sample size and congested data is needed.

Because this was the first field deployment of a temporary ramp meter, MoDOT had concerns about deploying ramp meters in highly congested areas. To minimize traffic impacts, MoDOT avoids closing lanes during peak hours in urban areas. Although all deployments in this study were in an urban area, they were conducted during off-peak hours. Future research could add to the existing study by including highly congested field sites.

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Appendix A

Sensitivity analysis results of 6-second threshold vs. 3-second threshold. According to Table A.2, there is as little as 0.54mph difference in speed differential means between the two threshold.

TABLE A.1

Speed Differentials(3 second)					
	Sample Size Lead/Follow	**Lead, Mean, mph**	**Follow, Mean, mph**	Lead Means, p-value	Follow Means, p-value
Ramp Meter Off	118/95	-9.65	-9.18	0.00	0.00
Ramp Meter On	144/85	-19.93	-18.64		

TABLE A.2 Speed differentials with leading/ following vehicles for both threshold values

	Lead, Mean, mph			**Follow, Mean, mph**		
	6 second	3 second	difference	6 second	3 second	difference
Ramp Meter Off	-10.34	-9.65	0.69	-9.78	-9.18	0.6
Ramp Meter On	-19.39	-19.93	0.54	-19.43	-18.64	0.79

Appendix B

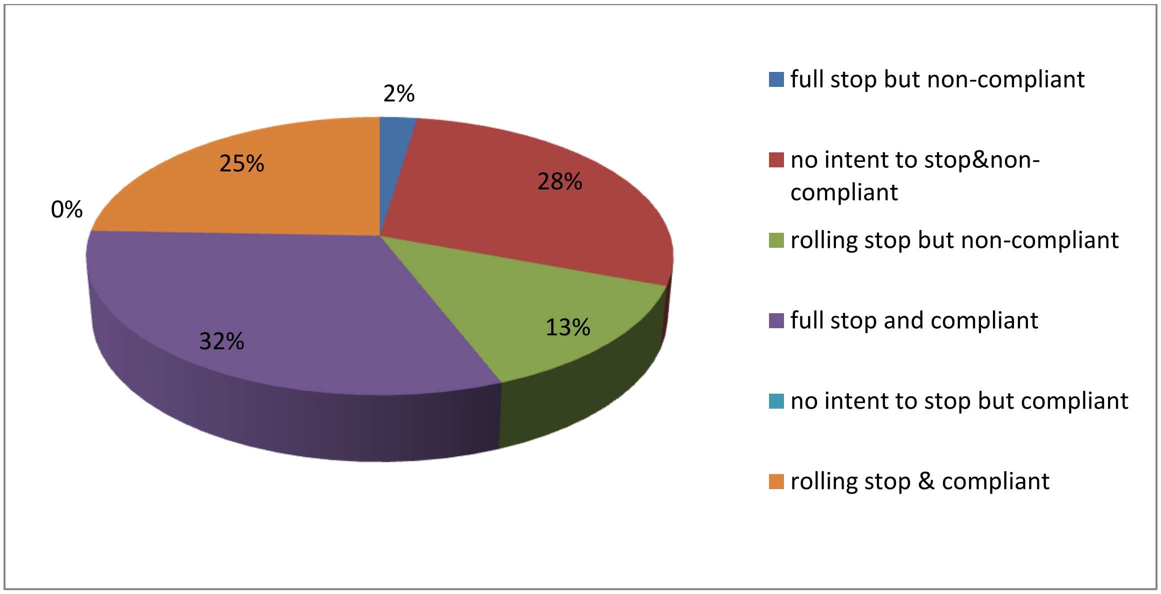

FIGURE B.1 compliance related driving behavior at Mile marker 126.6/WZ3

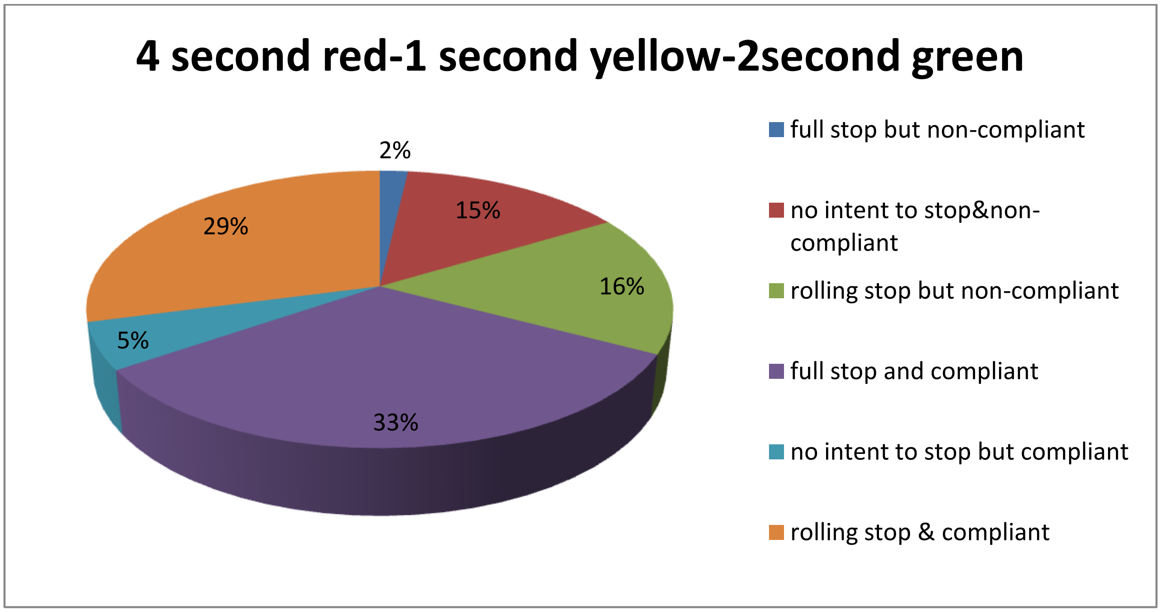

FIGURE B.2 compliance related driving behavior at Mile marker 125.6/WZ4

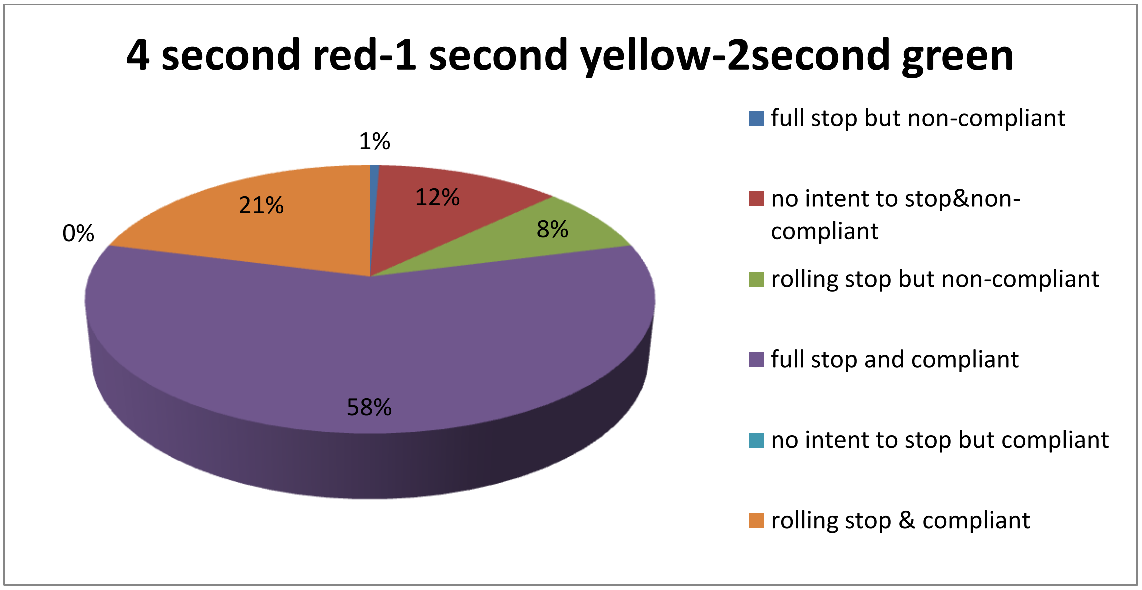

FIGURE B.3 compliance related driving behavior during Mile marker 129.0/WZ5

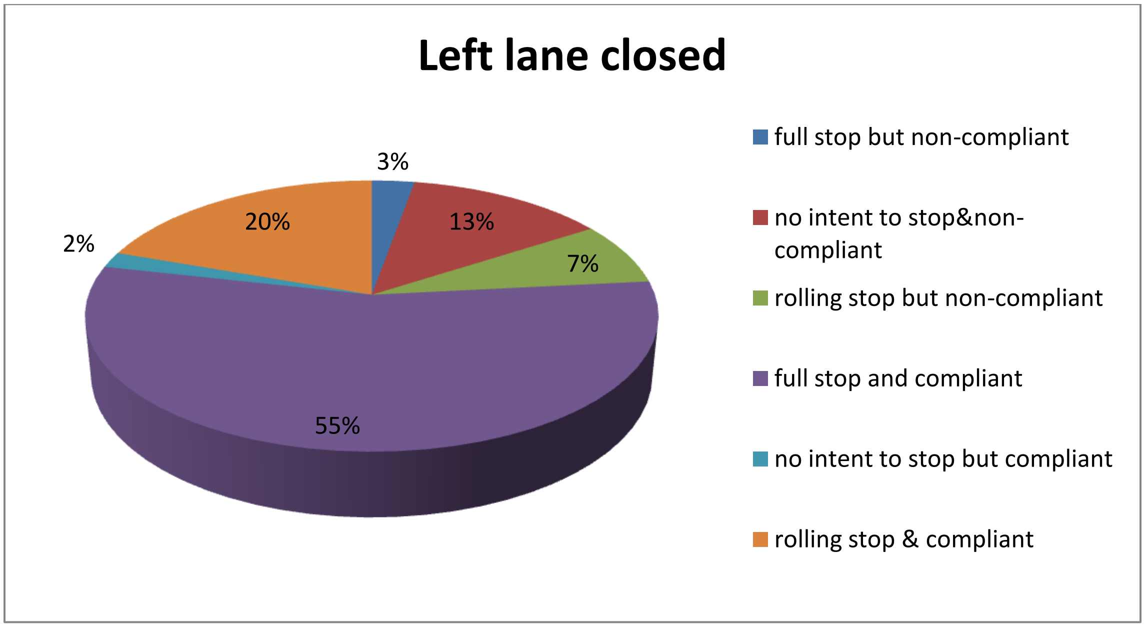

FIGURE B.4 compliance related driving behavior during on July/12th WZ6

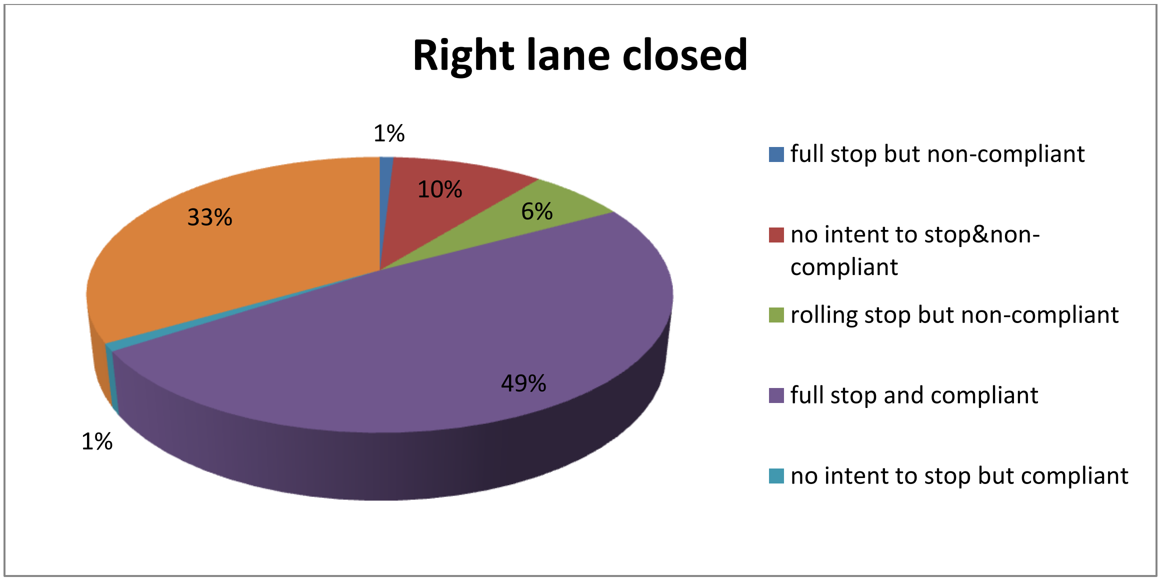

FIGURE B.5 compliance related driving behavior on July/13th WZ7