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Evaluation of the Effectiveness of ATM Messages Used During Incidents

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Final Report 2016-04

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16. Abstract (Limit: 250 words)

This project investigated the use of Intelligent Lane Control Signs based Active Traffic Management for Incident Management on a heavily traveled urban freeway. The subject of the research was the ILCS system on I-94 westbound in downtown Minneapolis. This location was selected because of the frequency of capacity reducing incidents occurring in this freeway segment. This research aimed to evaluate and quantify the effect the system has on drivers, specifically on inducing/directing a desirable lane selection behavior. The strength of various uses of the tool in managing traffic during incidents is explored instead of a general level of success in improving traffic. To achieve this goal, the centerpiece of this research was the comparison and modeling of the lane change rates under different strategies. This was a difficult task because all lane changes in the target freeway section had to be detected and geolocated. The research followed two main thrusts. The first was a detailed analysis of 28 incident events selected among approximately 481 events on record between 2012 and 2013. The second thrust was a statistical analysis testing a number of hypotheses prompted by questions proposed by the project Technical Advisory Panel. In general, it can be concluded that the use of ILCS for incident management has a significant effect on driver behavior and specifically in prompting proper lane selection under capacity reducing incidents.

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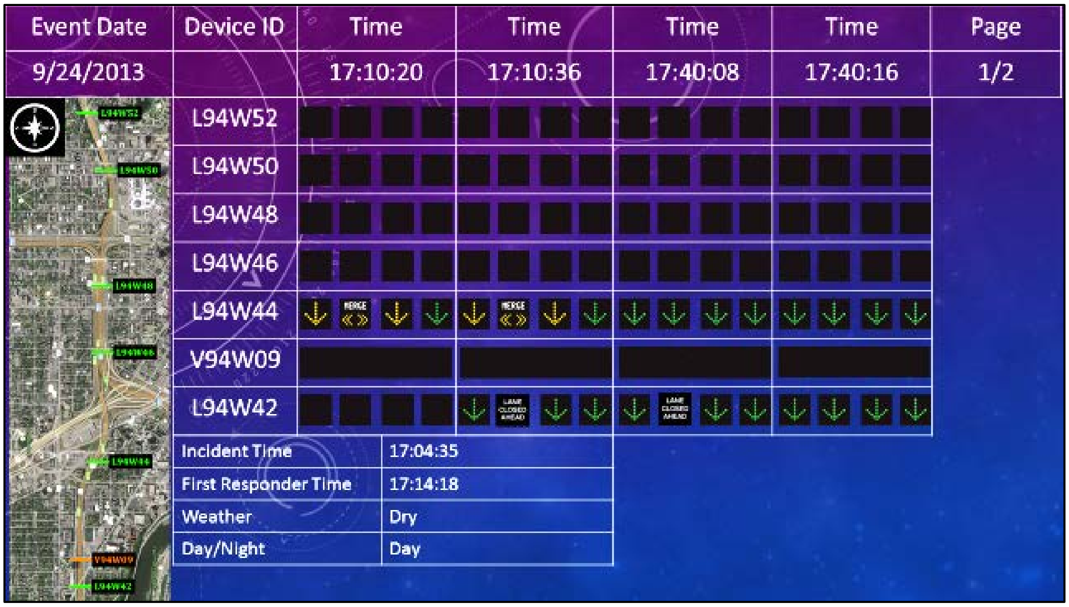
EXECUTIVE SUMMARY

Active Traffic Management (ATM) strategies have been deployed in cities all over the world to deal with rife roadway congestion and safety concerns. The Twin Cities metro area in Minnesota in particular, uses many resources to deal with the ever-changing roadway conditions. Two key components were developed as part of the implementation of the Intelligent Lane Control Signs (ILCS), Active Incident Management and Variable Speed Limits (VSL). This report presents an evaluation of the effectiveness of ILCS messages used during incidents on the safety of the high crash area (HCA) located on the westbound direction as the freeway goes through the Minneapolis Downtown area (I-94/I- 35W commons).

The goal of this project was to analyze the impacts of the ILCS system on driving behavior during non-recurrent congestion events. This was accomplished by using high-resolution video data collected along westbound Interstate 94 (I-94) using Minnesota Traffic Observatory (MTO) and Regional Traffic Management Center (RTMC) surveillance cameras. To target incidents along the HCA corridor, the VMS actuation log obtained from the RTMC was used to identify individual events categorized by time and gantry location. These events were counted from the VMS activation log based on the ILCS being activated, subsequent activations, and the ILCS being cleared. The events were thoroughly analyzed using loop detector data and lane change counts, which were collected manually. Lane change counts were amassed manually by using video overlays that indicated lane number and distance.

An event visualization was created for every event in 2012 and 2013 that met the research requirements. This was accomplished by displaying the ILCS messages graphically with respect to the gantry. Time-stamped configuration changes were shown on this graph to visually show what the gantry displayed above each lane and at what time. First responder time, incident time, weather conditions, and the status of the Dynamic Message Signs (DMS) were added to the figure to add further information about the event.



The research followed two main thrusts. The first was a detailed analysis of 28 incident events selected among approximately 481 events on record between 2012 and 2013. Given the detailed nature of the analysis, the reduction of only 28 events was possible with the given project's budget although the information and methodology exists for further analysis. The second thrust was a statistical analysis testing a number of hypotheses prompted by questions proposed by the project Technical Advisory Panel (TAP). Where the empirical analysis of each of the selected events offers a detailed deconstruction of the effect each particular scenario had on traffic and driver lane selection behavior, the statistical analysis tried to quantify and rank the different incident management alternatives. For brevity, the main project report contains a detailed description of four events while an appendix report has all events analyzed.

From both analysis thrusts, it can be concluded that the use of ILCS for incident management has a significant effect on driver behavior and specifically in prompting proper lane selection under capacity reducing incidents. Although the ILCS was envisioned as a unified system of equidistant successive gantries, based on the observations made in this research the inclusion of more than two gantries upstream of the incident in a response strategy is unnecessary since it does not seem to offer any additional benefit. This conclusion does not include the use of VSL three-quarters of a mile and farther upstream of the incident. An earlier research project showed that in the case of the advisory VSL used in Minnesota, they do not seem to be significantly affecting driving behavior. Therefore, using the two upstream ILCS for lane state information is much more effective while farther upstream gantries can be displaying VSL since they cause no harm.

In terms of specific scenarios of ILCS use, this research showed that specific sign configurations induce more lane changes than others. Specifically, the Use Caution sign has a relatively weak effect on lane changes especially in comparison to stronger messages like Merge, Lane Closed Ahead (LCA) and Lane Closed (LC). Perhaps intuitively, the Merge chevron sign seems to be the strongest sign for inducing lane changes upstream of an incident. The research has also shown that the combination of LCA followed by a Merge chevron on successive gantries is most effective. The analysis as well as the empirical evidence show that the visual presence of first responders like FIRST and State Patrol vehicles has an observable positive effect on lane change behavior but not as effective as instructions on an ILCS. This makes sense since although the presence of first responders is a direct confirmation of the incident presence, it does not provide information to the drivers on which lane to choose. As stated in the previous paragraph, the combination of directed information along with the confirmation from the presence of units on scene is most effective. In conclusion, the impact of the first responder is strong, but not as strong as a 'strong' ILCS message, and the presence of a first responder does not effectively replace the ILCS system.

Finally, from all the events observed, a qualitative observation of ILCS operation in view of heavy congestion can be made. Specifically, the ILCS are becoming ineffective under stop-and-go conditions. Beyond the simple logic of this statement, stemming from the fact that a lane selection system stops being effective when lane changes are impossible, there is a finer interesting detail of note. It was observed that in most cases the ILCS were capable of emptying the incident lane well upstream of the obstruction caused by the incident, even when the next lane was considerably congested. As noted in prior research on the merits of work zone zipper-merge in such situations, wasting storage by emptying a lane early may not be the most efficient strategy. Overall, utilizing the ILCS to induce lane changes out of the incident lane can not only become ineffective but also may be detrimental if the freeway section is under stop-and-go conditions. After a certain point, the preferred operational strategy may be to switch off the ILCS messages or display an innocuous message rather than instruct drivers to change lanes. The latter is even more relevant if a first responder protecting the incident scene is already present.

CHAPTER 1: INTRODUCTION

Active Traffic Management (ATM) strategies have been deployed in cities all over the world to deal with rife roadway congestion and safety concerns. The Twin Cities, MN, in particular, uses many resources to deal with the ever changing roadway conditions. Two key components were developed as part of the implementation of the Intelligent Lane Control Signs (ILCS), Active Incident Management and Variable Speed Limits (VSL). Active Incident Management is a relatively new tool for traffic management. So far, two corridors in the Twin Cities have been equipped with the necessary infrastructure required by these systems, I-94 and I-35W. Active Incident Management aims to proactively warn drivers upstream of an incident by displaying various signs above each lane to alert drivers and direct them to the best route through the corridor. Driver compliance to these signs is paramount for the effectiveness of this strategy.

Figure 1-1. Gantry displaying ILCS messages.

The VSL system on I-94 was the subject of an evaluation of its operational effectiveness in an earlier project (Hourdos et al. 2014) while this report focuses on the incident management component of the ATM strategies. This report presents an evaluation of the effectiveness of ATM messages used during incidents on the safety of the High Crash Area (HCA) located on the westbound direction as the freeway goes through the Minneapolis Downtown area (I-94/I- 35W commons). The HCA, a nearly two-mile segment of westbound I-94 along the south edge of downtown Minneapolis, experiences more crashes than any other freeway location in the state of Minnesota. This region includes a significant shockwave-generating bottleneck located at the merge point of I-94 and I-35W northbound. Crash events are observed on average once every two days, making the corridor ideal for collecting significant safety data within a short period of time. The project capitalized on a unique field laboratory, established in 2002 by the Minnesota Traffic Observatory, in this location. The I-94 Field Lab instrumentation provided a uniquely detailed picture of the high crash area both in terms of observations, with its seamless surveillance coverage, and traffic measurements.

The goal of this project is to analyze the impacts of the ILCS system on driving behavior during non-recurrent congestion events. This was accomplished by using high resolution video data collected along westbound Interstate 94 (I-94) using Minnesota Traffic Observatory (MTO) and Regional Traffic Management Center (RTMC) surveillance cameras. In order to target incidents along the HCA corridor, the VMS actuation log obtained from the RTMC was used to identify individual events categorized by time and gantry location. These events were counted from the VMS activation log based on the ILCS being activated, subsequent activations, and the ILCS being cleared. The events were thoroughly analyzed using Loop detector data and lane change counts which were collected manually. Lane change counts were amassed manually by using video overlays which indicated lane number and distance.

These data were then combined in a database and were processed using statistical modeling techniques in order to produce multi-variable linear regression models describing the relationships between various ILCS configuration parameters and driver behavior (specifically lane changes). A series of hypotheses were developed based on intuitive understanding of the operation of the ILCS system. Each of these hypotheses were explored based on the available data and, where possible, models were developed. From the significant variables within these models, an understanding of the relationship between model parameters and lane changes is made. From these models, larger conclusions are reached as to the effectiveness of the ILCS and specifically the importance of sign configuration and other non-ILCS factors.

This report begins with a description of the site under investigation and a description of the data collected for the purposes of this research. The report follows with the methodologies for the data reduction. Next, the final event set is presented and several of the events are thoroughly analyzed. The statistical analyses utilized in this research are presented next followed by the hypotheses tests, results, and conclusions.

CHAPTER 2: DATA SOURCES

2.1 Area of Interest

Interstate 94 is the main artery connecting Minneapolis and St. Paul, and as such is a highly traveled corridor. It carries an average daily traffic volume of more than 80,000 vehicles in each direction. This study is conducted in the westbound section of I-94 from Riverside Avenue to the Lowry Hill Tunnel. A 1.7 mile section of the interstate from 11th Avenue to the Lowry Hill Tunnel has been identified by MnDOT as the highest crash area in the state. The crash rate in this corridor for the study period was 4.81 crashes/MVM (million vehicles miles) which is roughly equivalent to one crash every two days. This corridor was equipped with the ILCS as a strategy to deal with pervasive congestion and safety concerns.

Figure 2-1. I-94/I-35W commons in Minneapolis.

2.2 Video Coverage from Region of Interest

The region of interest is the corridor of I-94 westbound from Riverside Avenue to the Lowry Hill Tunnel. Along this section of I-94 there are eight rooftop cameras controlled by the MTO referred to as the Beholder system. Beholder is made up of cameras emplaced on three rooftops along the corridor. Four cameras are located on an apartment building at 1707 3rd Ave S Minneapolis, MN (designated Roadstripe). The two Athos-designated cameras are located at Augustana, a senior living center located at 1020 E 17th St Minneapolis, MN. Two cameras are located on a Minneapolis Public Housing building located at 730 Cedar Ave Minneapolis, MN (designated Porthos). Supplementing these cameras are sixteen RTMC cameras which were captured on the MTO's Galileo system, consisting of four-channel recording devices. Galileo 1 contains the DVR1 videos which contains four separate cameras DVR1 – Cam1, DVR1 – Cam2, DVR1 – Cam3, and DVR1 – Cam4. Galileo 2, 3, and 4 have the same organization. The Galileo videos' internal naming scheme and their locations are shown in Table 2-1. Figure 2-1 shows the locations of the Beholder and Galileo cameras and the stretch of I-94 that they observe. This corridor contains six ILCS gantries of interest (L94W42 – L94W52) shown in further detail later in this report.

Table 2-1. Galileo video naming scheme.

RTMC Device ID	MTO Galileo ID	Location
C8321	DVR1 - Cam1	I-94/Groveland Ave N
C8331	DVR1 - Cam2	I-94/1st Ave
C8340	DVR1 - Cam3	I-94/W of Portland Ave N
C8350	DVR1 - Cam4	I-94/E of Portland Ave N
C8351	DVR2 - Cam1	I-94/Park Ave
C8353	DVR2 - Cam2	I-94/T.H. 55 S
C8361	DVR2 - Cam3	i-94/Riverside Ave
C8381	DVR2 - Cam4	I-94/Huron Ave SE
C918	DVR3 - Cam1	I-394/I-94 S
C831	DVR3 - Cam2	I-94/Tunnel West 3N
C830	DVR3 - Cam3	i-94/Tunnel West 2N
C829	DVR3 - Cam4	I-94/Tunnel West 1N
C832	DVR4 - Cam1	I-94/Hennepin - Lyndale
C835	DVR4 - Cam2	I-94/Portland Ave N
C836	DVR4 - Cam3	I-94/Cedar Ave S
C837	DVR4 - Cam4	I-94/Riverside Ave S

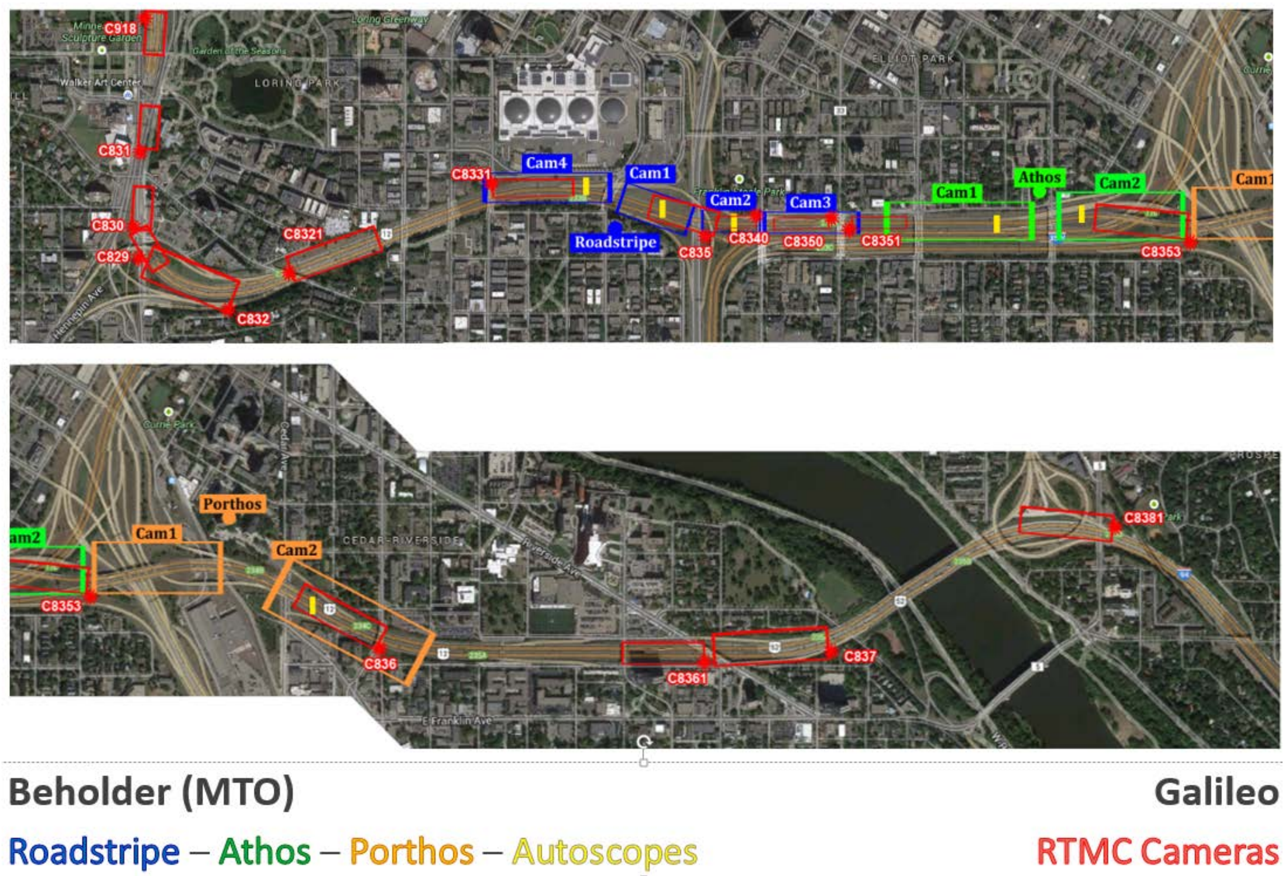


Figure 2-2. MTO and RTMC recording locations and approximate fields of view.

2.3 VMS Activation Log

The VMS activation log was obtained from the RTMC which provides a history of every activation from 2012 and 2013. The log contains VSL and ILCS actuations for all gantries in the

Twin Cities, not just the region of interest. The VMS log was loaded into a database and queries were developed to select only actuations along the corridor of interest and filter out unrelated activations (text messages, Variable Speed Limit activations, etc.). The criterion for what data was excluded is explained later in this report. An example of the log after the VSL actuations and the gantries not relevant to this project are removed is shown in Figure 2-3.

Cleaned_Up_Events

Device ID	event date	Date	Time	description	line 1
L94W40	11/9/2012 6:06:19 PM	2012-11-09	18:06:19	LCS CLEARED	
L94W40	11/9/2012 6:08:19 PM	2012-11-09	18:08:19	LCS CLEARED	
L94W40	11/9/2012 6:10:19 PM	2012-11-09	18:10:19	LCS CLEARED	
L94W40	11/9/2012 6:18:19 PM	2012-11-09	18:18:19	LCS CLEARED	
L94W50	11/9/2012 6:25:49 PM	2012-11-09	18:25:49	LCS CLEARED	
L94W46	11/9/2012 6:25:54 PM	2012-11-09	18:25:54	LCS DEPLOYED	LANE_OPEN USE_CAUTION MERGE_BOTH USE_CAUTION
L94W44	11/9/2012 6:26:13 PM	2012-11-09	18:26:13	LCS DEPLOYED	LANE_OPEN USE_CAUTION MERGE_BOTH USE_CAUTION
L94W44	11/9/2012 6:26:40 PM	2012-11-09	18:26:40	LCS DEPLOYED	LANE_OPEN LANE_OPEN USE_CAUTION MERGE_LEFT
L94W46	11/9/2012 6:26:58 PM	2012-11-09	18:26:58	LCS DEPLOYED	LANE_OPEN LANE_OPEN USE_CAUTION MERGE_LEFT
L94W46	11/9/2012 6:29:59 PM	2012-11-09	18:29:59	LCS DEPLOYED	LANE_OPEN LANE_OPEN LANE_OPEN USE_CAUTION
L94W44	11/9/2012 6:30:04 PM	2012-11-09	18:30:04	LCS CLEARED	
L94W38	11/9/2012 6:41:49 PM	2012-11-09	18:41:49	LCS CLEARED	
L94W40	11/9/2012 6:43:19 PM	2012-11-09	18:43:19	LCS CLEARED	
L94W40	11/9/2012 6:44:19 PM	2012-11-09	18:44:19	LCS CLEARED	
L94W42	11/9/2012 6:50:49 PM	2012-11-09	18:50:49	LCS CLEARED	
L94W44	11/9/2012 6:53:19 PM	2012-11-09	18:53:19	LCS CLEARED	
L94W44	11/9/2012 6:54:19 PM	2012-11-09	18:54:19	LCS CLEARED	
L94W40	11/9/2012 6:56:29 PM	2012-11-09	18:56:29	LCS DEPLOYED	LANE_OPEN LANE_OPEN USE_CAUTION MERGE_LEFT
L94W38	11/9/2012 6:56:49 PM	2012-11-09	18:56:49	LCS CLEARED	
L94W38	11/9/2012 6:57:09 PM	2012-11-09	18:57:09	LCS DEPLOYED	LANE_OPEN LANE_OPEN USE_CAUTION MERGE_LEFT
L94W48	11/9/2012 7:00:19 PM	2012-11-09	19:00:19	LCS CLEARED	
L94W48	11/9/2012 7:02:19 PM	2012-11-09	19:02:19	LCS CLEARED	
L94W48	11/9/2012 7:04:19 PM	2012-11-09	19:04:19	LCS CLEARED	
L94W40	11/9/2012 7:05:05 PM	2012-11-09	19:05:05	LCS CLEARED	
L94W38	11/9/2012 7:05:08 PM	2012-11-09	19:05:08	LCS CLEARED	
L94W48	11/9/2012 7:05:19 PM	2012-11-09	19:05:19	LCS CLEARED	
L94W40	11/9/2012 7:06:19 PM	2012-11-09	19:06:19	LCS CLEARED	
L94W48	11/9/2012 7:08:49 PM	2012-11-09	19:08:49	LCS CLEARED	
L94W48	11/9/2012 7:10:19 PM	2012-11-09	19:10:19	LCS CLEARED	
L94W46	11/9/2012 7:15:04 PM	2012-11-09	19:15:04	LCS CLEARED	
L94W48	11/9/2012 7:17:19 PM	2012-11-09	19:17:19	LCS CLEARED	
L94W44	11/9/2012 7:17:19 PM	2012-11-09	19:17:19	LCS CLEARED	
L94W46	11/9/2012 7:20:19 PM	2012-11-09	19:20:19	LCS CLEARED	
L94W48	11/9/2012 7:21:49 PM	2012-11-09	19:21:49	LCS CLEARED	
L94W46	11/9/2012 7:22:19 PM	2012-11-09	19:22:19	LCS CLEARED	

Figure 2-3. Sample of VMS log entries.

2.4 Loop Detector data from MnDOT – Speed/Density/Volume data extraction

The average lane speeds, average lane densities, and average lane volumes corresponding to the time of each incident in the video data were extracted from the Regional Transportation Management Center (RTMC) loop detector database. For the purpose of this report, the *DataExtract* Program provided by MnDOT, was the application used for the data extraction, since this tool provides average values of speed/density/volume at given times. The location and identification number of loop detectors, dates of records from video collection, time ranges at which the video was collected and the frequency of the desired average speed/density/volume data, are required as input for the data extraction.

2.5 Data Collection Summary

The vast majority of the study period of 2012 and 2013 was covered by all the data sources indicated above. The study period was later changed to only include 2013. During the course of the project 2012 was removed because the system operation was still in its early stages. It wasn't until 2013 that there were clear guidelines for the activations. Both the ILCS records and data retrieved from MnDOT's loop detector network include all dates throughout the project window, although there are some small, intermittent gaps in data among some loop detectors due to malfunction and construction. From the ILCS actuation records, events were identified and charted (as will be described below). 159 events were identified from 2012 and 332 events were identified from 2013.

The Beholder system was reinitiated beginning in the spring of 2012 and collected data between 10 AM and 8 PM each week day (Monday through Friday). Intermittent minor maintenance outages of several days occurred throughout the study period. The Galileo system was developed and implemented starting in the summer of 2012, with I-94 coverage beginning in July. During the winter of 2012, Galileo underwent major maintenance causing a gap in data collection during most of December 2012. Full coverage resumed in January 2013 and continued with only minor interruptions until the conclusion of 2013. Galileo collected video from 11 AM through 8 PM on weekdays, similar to the Beholder system. In sum, approximately 40 terabytes of video from the Beholder and Galileo systems were collected across 2012 and 2013.

CHAPTER 3: DATA REDUCTION

3.1 Event Identification

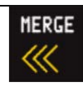
In order to evaluate the effectiveness of the ILCS during incidents several different pieces of information were gathered. Events or incidents were observed manually within the VMS log obtained from the RTMC. The first task was to isolate ILCS actuations from the VMS log. The log contained significant data not relevant to this project including: gantries not in the corridor, VSL actuations, events not in our time window of interest, and actuations displaying an 'UNKNOWN'. The methodology for isolating events from the VMS log was accomplished as follows.

- Events were narrowed down to the corridor of interest shown in Figure 3-1. The gantries included in this project indicated by their device ID are as follows.
    1. L94W52
    2. L94W50
    3. L94W48
    4. L94W46
    5. L94W44
    6. L94W42

Figure 3-1. ILCS gantry locations along I-94 westbound.

- Events were then narrowed down by the time window of interest. Since video data was limited to certain daytime hours, the event time is constrained to only include event times from 10AM to 8PM. Therefore, the events from 8PM to 10AM were excluded. Exceptions were made for events that carried over from the previous or subsequent hour. For example, an event that started at 9:45 AM and ended at 10:30 PM would be included in this project. Likewise, an event that started at 7:45 PM and ended at 8:15 PM would also be included.
- To have a clear cut-off between events, the first deployment of the gantry 'LCS DEPLOYED' and the final cleared message 'LCS CLEARED' needed to be observed.
- Events were chosen based on the specific signs that were portrayed. VSL actuations and 'UNKNOWN' actuations were removed, so only ILCS actuations remained. The ILCS signs are displayed in Table 3-1. Note that there are two versions of Lane Closed Ahead, one featuring a yellow 'x' and one using text only.

Table 3-1. ILCS sign icons and log codes for all indications.

Sign	Data Label
	DARK
	LANE_OPEN
	USE_CAUTION
	MERGE_RIGHT
	MERGE_LEFT
	MERGE_BOTH
	LANE_CLOSED_AHEAD
	LANE_CLOSED_AHEAD
	LANE_CLOSED

3.2 Event Visualization

In order to track the progression of the ILCS event, a visualization aid was generated for each event. This was accomplished by creating a PowerPoint presentation where separate events are tabulated according to the event date, device ID, and time. Each page contains four major columns (labeled with a 'Time' at the top) and each display a unique ILCS configuration state. Additional pages are used for additional states. An example of an event is shown in Figure 3-2 and Figure 3-3. An event visualization was created for every event in 2012 and 2013 that met the criteria above. This was accomplished by displaying the ILCS messages graphically with respect to the gantry. Time-stamped configuration changes were shown on this graph to visually show what the gantry displayed above each lane and at what time. First responder time, incident time, weather conditions, and the status of the Dynamic Message Signs (DMS) were added to the events to add further information about the event.

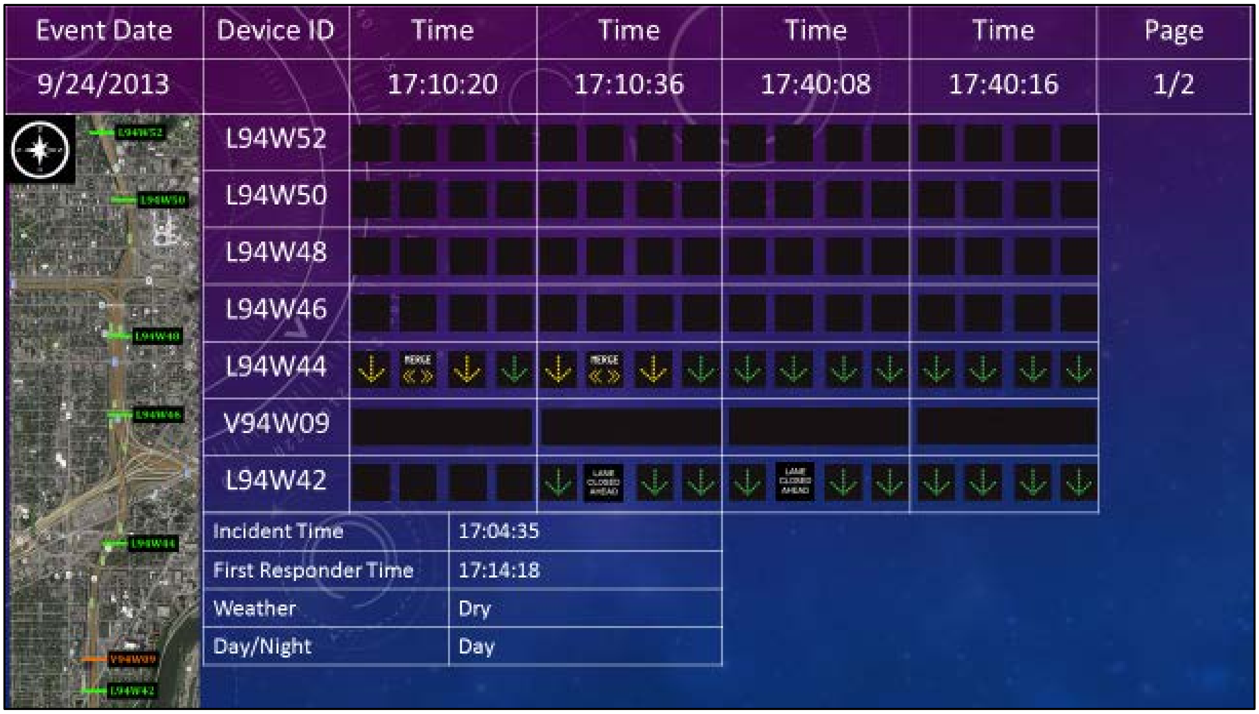


Figure 3-2. Sample event visualization - slide 1.

Figure 3-3. Sample event visualization - slide 2.

3.3 Lane Change Analysis Methodology

In addition to the analysis methodologies detailed above, lane change data were extracted from video collected along the I-94 corridor. Using a GIS framework, a single continuous polyline was created from an arbitrary point far downstream from the main region of interest. From this arbitrary point (which falls on the north side of the Lowry Hill Tunnel), 10 meter increments were marked along the entirety I-94 westbound to a second arbitrary end point near Highway 280. By including this entire area, all possible camera views used in relation to events extracted for analysis are encompassed.

These 10-meter increments were used as the basis of a lane change counting methodology. Using cameras overlooking the freeway, a set of video overlays were developed to show the location of each increment in relation to the camera view. For each camera a screenshot was taken and ortho-rectified using image correction software. This rectification process produced an adjusted image which captures the region of freeway within the camera's view as though the camera was directly above the freeway. This corrects the distances in the image so that each pixel represents a constant distance on the roadway.

In each ortho-rectified image, landmarks were used as reference points to map the freeway and place the evenly-spaced 10 meter marks so that they matched the GIS point set. With each increment noted on the rectified image, marks were added to the actual camera screenshot accounting for perspective. The end result of these efforts can be seen in Figure 3-4 below.

As can be seen in the figure, in addition to the increment markings, lanes were highlighted and numbered and additional reference lines were added to ensure that the overlay matched the view captured by the camera. In most cases the camera views shifted slightly across the capture period, resulting in multiple slightly shifted overlays for each location.

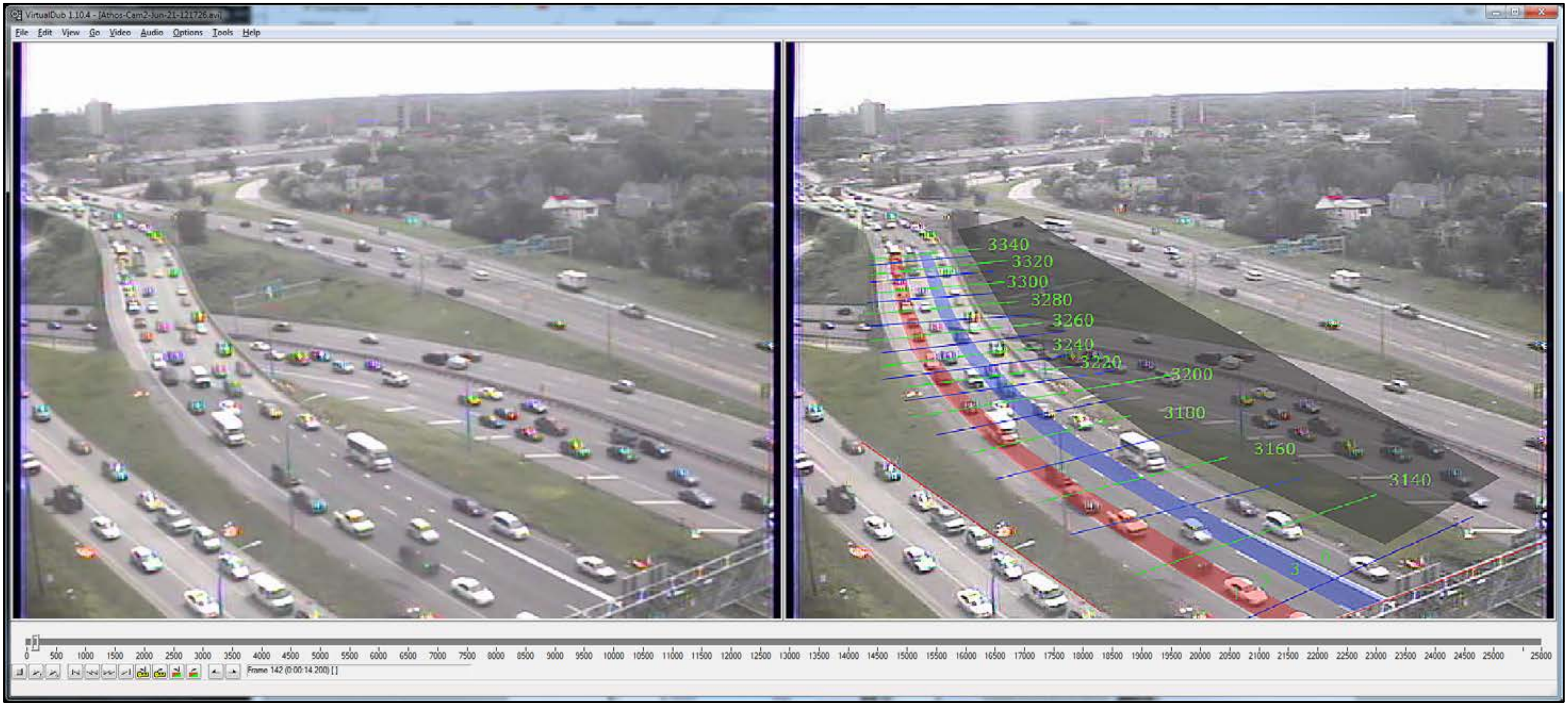


Figure 3-4. Ortho-rectified distance overlays for lane change geo-location.

By adding the overlay to each video image, lane changes into and out of targeted lanes were collected for ILCS events. Lane changes were noted at the point when a vehicle entered into an adjacent lane far enough to 'control' the lane. In most cases this was when the front of the vehicle had traversed 75% of the way to fully over the lane line. An example can be seen in Figure 3-5 with the truck changing lanes at marker 3240 in the middle of the screen. Lane changes were noted in both space and time, allowing for further analysis as will be described further in the report.

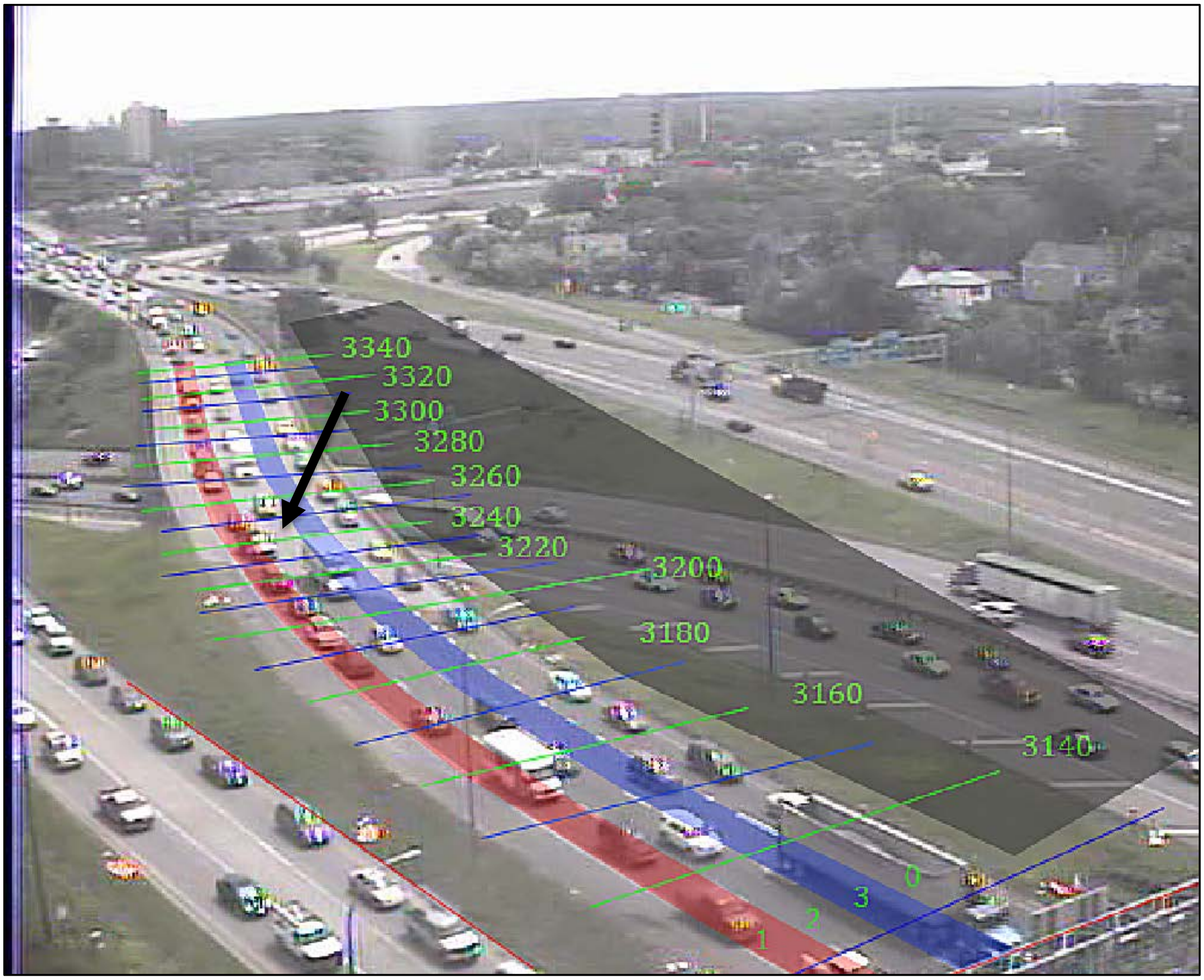


Figure 3-5. Example of a lane change, marker 3240.

CHAPTER 4: FINAL EVENT SET

4.1 Final Event Sample Set

A final set of events were identified for incorporation into analysis efforts. The events chosen were selected to cover as many sign configurations as possible while maintaining sufficient sampling for the statistical modeling methodologies (further described later in the report). A short description of all the events is shown in Table 4-1. The research team set out to analyze 30 events; a final total of 28 events were selected for detailed analysis. Each event was carefully chosen based the location of incident, video coverage, time and length of the event, gantries activated, and the configuration of the signs. All events from 2012 were ultimately eliminated from analysis since during that period the techniques used by the RTMC were highly variable. Throughout 2013, RTMC use of the system was consistent. From these constraints, a priority ranking of all of the events obtained for this project allowed for the selection of these events.

4.2 Event Examples

From this final list of events, a subset of events were chosen to represent the types of events contained in this project. While all of the events are unique, these events embody the final event set and invoke some questions which will be answered in the statistical analysis later in the report.

4.2.1 Sample Event 1: 8/13/2013 16:46:13 – 17:23:11

This event was chosen to illustrate the effect of one of the most commonly used messages, the Use Caution signal. This event includes a single Use Caution sign deployed over lane three at the 11th Avenue gantry. Vehicles involved in an incident moved to the left shoulder just upstream of Park Avenue, making the use of that gantry infeasible. The next upstream gantry was deployed with a Use Caution, but the lane remained open.

Table 4-1 . Set of final events for detailed analysis.

Date	**Event Time**	**Duration**	**Number of Gantries Activated**	**Number of States**	**Incident Location**	**Incident Time**	**First Responder Arrival Time**
1/29/2013	11:07:39 – 11:22:12	15 min	1	2	West of Cedar Ave	Before 11:00:00	11:12:23
2/7/2013	16:11:35 - 16:31:41	20 min	1	1	Portland Ave	16:06:35	16:09:36
2/18/2013	13:24:51-13:27:30	3 min	2	1	Groveland Ave	13:22:29	NA
3/4/2013*	13:21:55-13:46:24	24 min	1	1	Lowry Hill Tunnel	Not Observable	Not Observable
3/15/2013	15:28:19 - 15:48:43	20 min	2	1	11th Ave	15:23:15	15:25:39
3/15/2013	18:30:48 - 19:02:44	32 min	3	2	11th Ave	18:29:05	18:36:25
3/21/2013	16:24:38 - 17:12:10	48 min	1	1	Above 35W S	16:12:56	16:27:56
4/5/2013	18:57:14 - 19:03:50	6 min	2	1	Park Ave	18:55:58	19:00:38
5/1/2013	16:32:25-16:43:46	11 min	2	3	Above H 55	16:25:57	16:36:50
5/2/2013	18:45:35 - 19:30:58	45 min	1	1	Park Ave	18:39:18	18:46:08
5/3/2013	11:46:12-12:00:28	14 min	1	1	Portland Ave	11:23:08	11:27:07
5/22/2013	18:31:25-19:13:57	42 min	2	3	Groveland Ave	18:30:26	18:34:48
5/24/2013	17:40:13 - 17:47:23	7 min	1	1	Portland Ave	17:34:26	17:43:54
5/31/2013	14:34:58 - 14:42:12	7 min	1	1	11th Ave	14:26:30	14:34:49
6/21/2013	12:22:26 - 13:34:46	72 min	3	4	Portland Ave	12:03:32	12:27:45
7/1/2013	16:39:50 - 16:48:53	9 min	2	1	Portland Ave	16:13:19	16:43:18
8/2/2013	17:24:06 - 17:55:57	32 min	2	2	Portland Ave	17:20:59	17:38:48
8/12/2013	15:46:03 - 15:56:29	10 min	1	1	Above H 55	15:14:04	15:51:10
8/13/2013	16:46:13 - 17:23:11	37 min	1	1	Park Ave	16:38:09	17:02:20
8/14/2013	18:47:09 - 19:12:12	25 min	2	1	Portland Ave	18:43:45	18:54:50
8/21/2013	12:33:09 - 13:22:44	49 min	4	4	Portland Ave	12:27:30	12:37:24
8/27/2013	14:45:57-15:29:36	43 min	2	4	Above H 55	14:42:52	14:50:46
9/5/2013	13:45:37-13:56:28	11 min	3	3	Park Ave	13:35:27	13:45:15
9/19/2013	12:59:50 - 13:01:15	2 min	1	1	Portland Ave	12:52:16	12:58:30
9/24/2013	17:10:20-17:42:48	22 min	2	1	Above H 55	17:04:35	17:14:18
12/18/2013	15:54:30-18:19:36	145 min	2	2	3rd Ave	15:46:28	15:56:40
12/27/2013	14:54:41-15:30:40	36 min	2	1	Above H 55	14:53:57	14:59:57
12/31/2013	10:59:47-11:06:51	7 min	2	1	Portland Ave	Before 11:00:00	NA

*Event occurred in the Lowry Hill tunnel and was unobservable

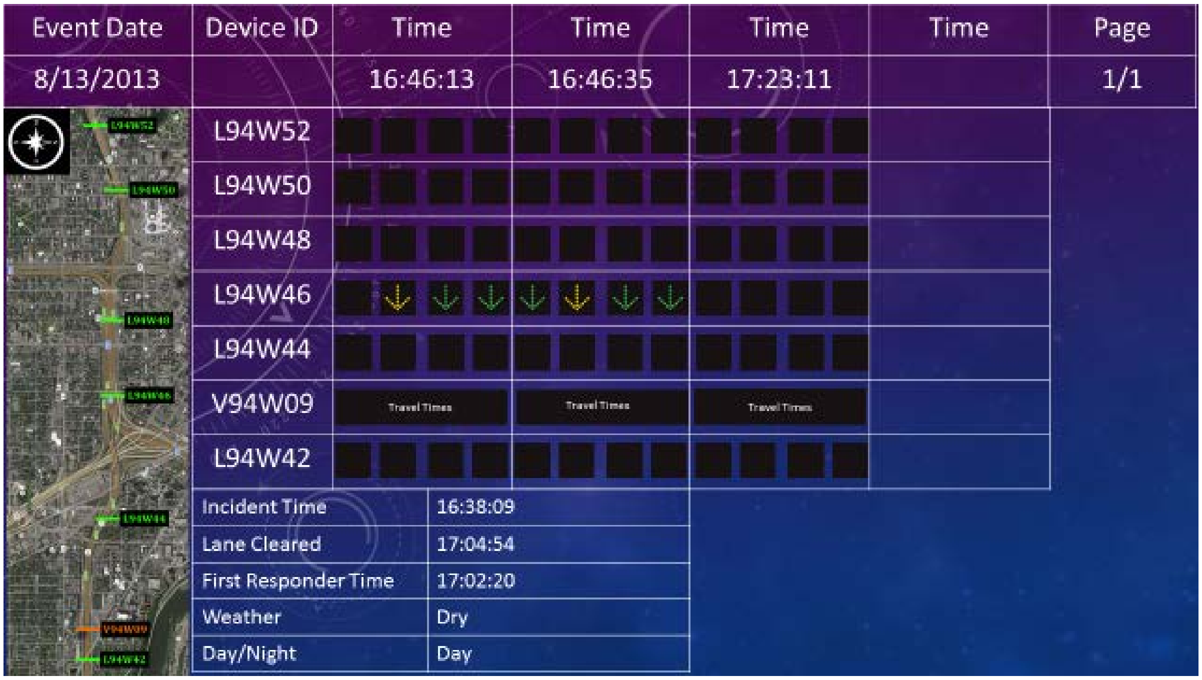


Figure 4-1. Event slide for 8/13/2013.

Lane three showed a drop in volume and speed after the shockwave from the incident reached 11th Avenue. Speeds and volumes recovered after the implementation of the ILCS, but remained highly variable over the remainder of the event. Lanes one and two were largely unaffected by the presence of the incident vehicles on the shoulder and the deployment of the ILCS.

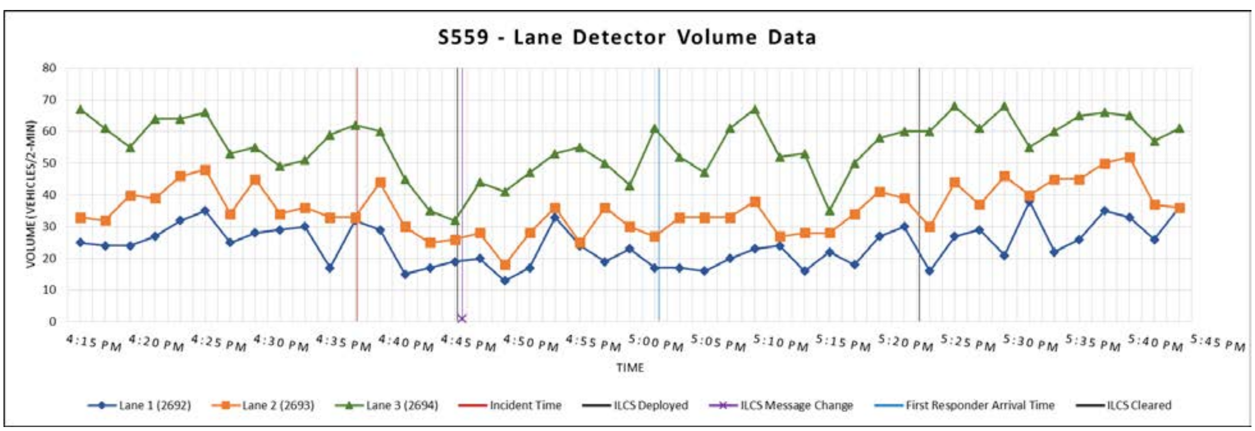


Figure 4-2. Volume data at Station 559 (upstream of 11th Avenue) - 8/13/2013.

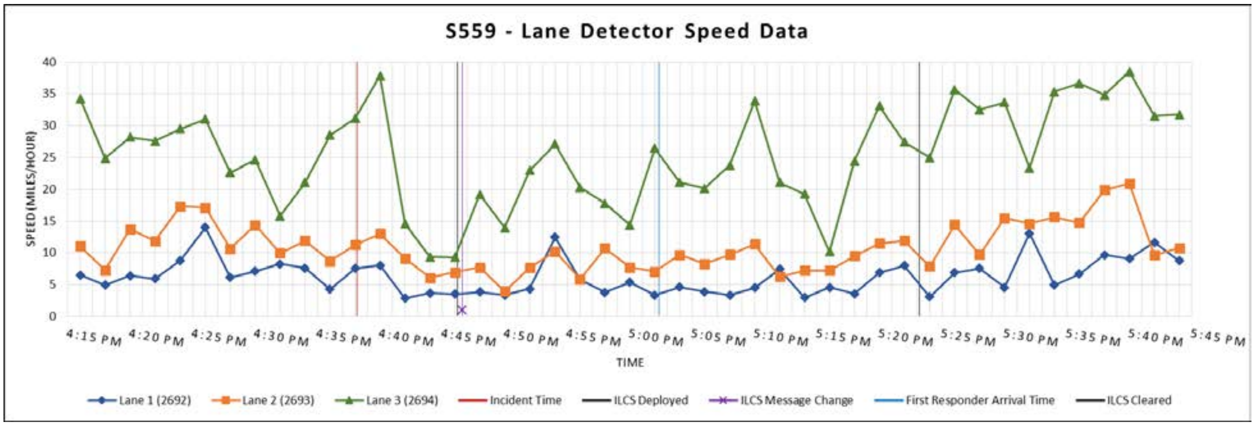


Figure 4-3. Speed data at Station 559 (upstream of 11th Avenue) - 8/13/2013.

The lane changes collected for this event show little evidence of behavioral modification due to the presence of the ILCS. Upstream of the I-35W exit ramp, a large region of lane changes can be seen as vehicles seek or avoid the exit. The region further downstream, just past the 11th Avenue gantry, shows a small number of lane changes out of lane three, but these were countered by vehicles entering lane three.

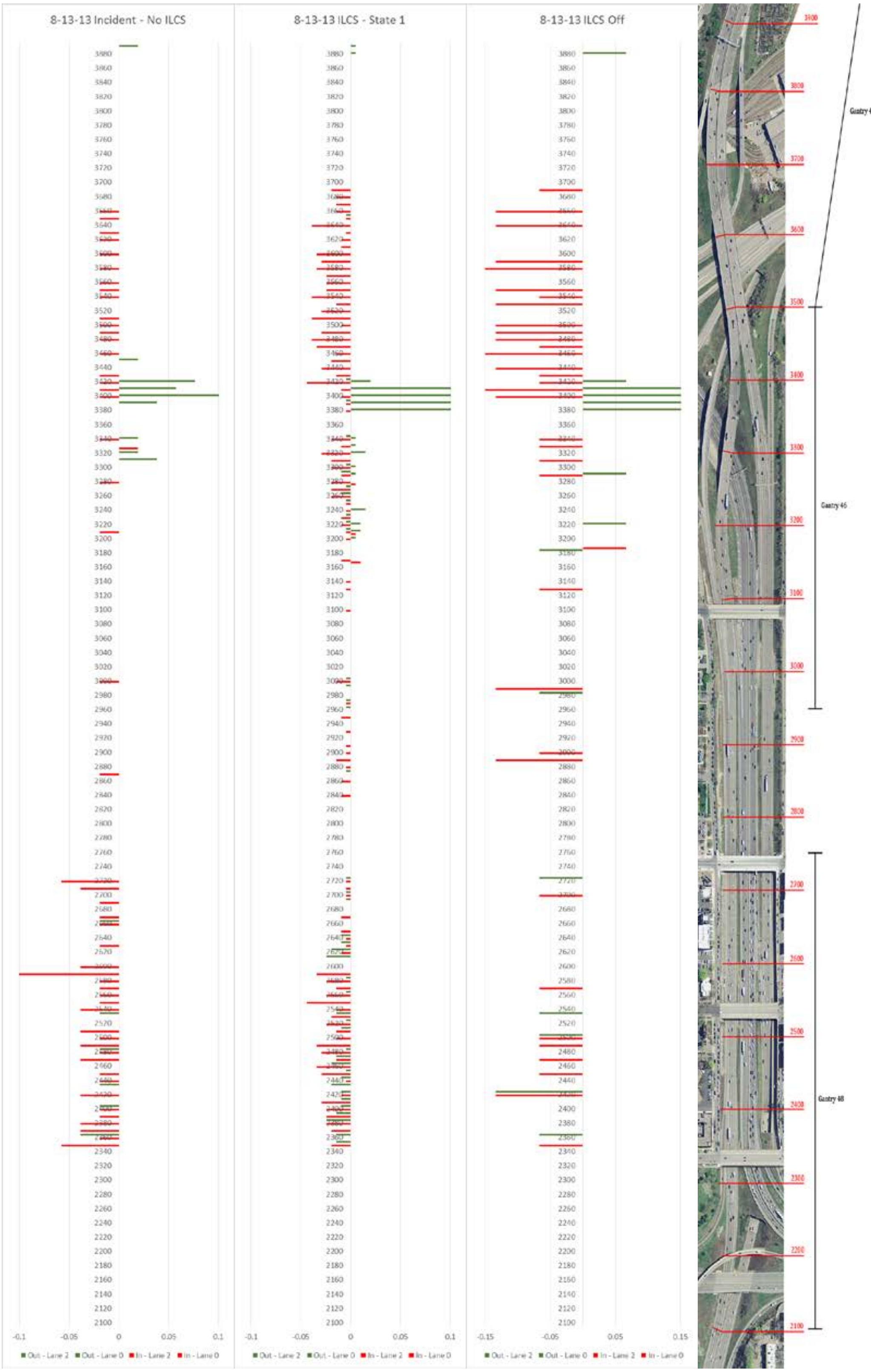


Figure 4-4. Lane changes by state for 8/13/2013.

4.2.2 Sample Event 2: 8/2/2013 17:24:06 – 17:55:57

This event was chosen to show the effects of the Merge Chevron and the Merge Chevron with a Lane Closed Ahead upstream on lane changing behavior. This event involves three vehicles at the High Crash Area near Portland Avenue. Shortly after the crash, a Merge sign was placed over lane one at Park Avenue, preceded by a Lane Closed Ahead indication at 11th Avenue. These signs remained in place for several minutes until debris from the road was sufficiently cleared for lane one to reopen. The Merge was then replaced by a Use Caution sign, and the 11th Avenue gantry was deactivated. The single Use Caution sign remained until the incident vehicles were cleared with the help of first responders.

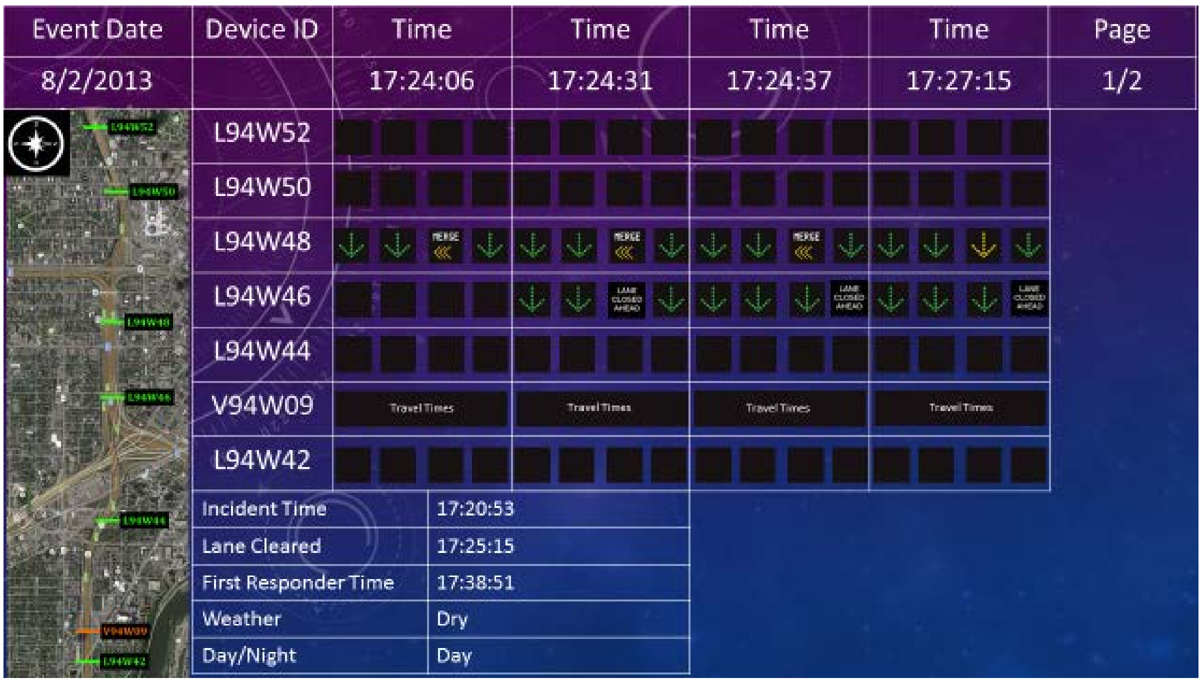


Figure 4-5. Event slide for 8/2/2013.

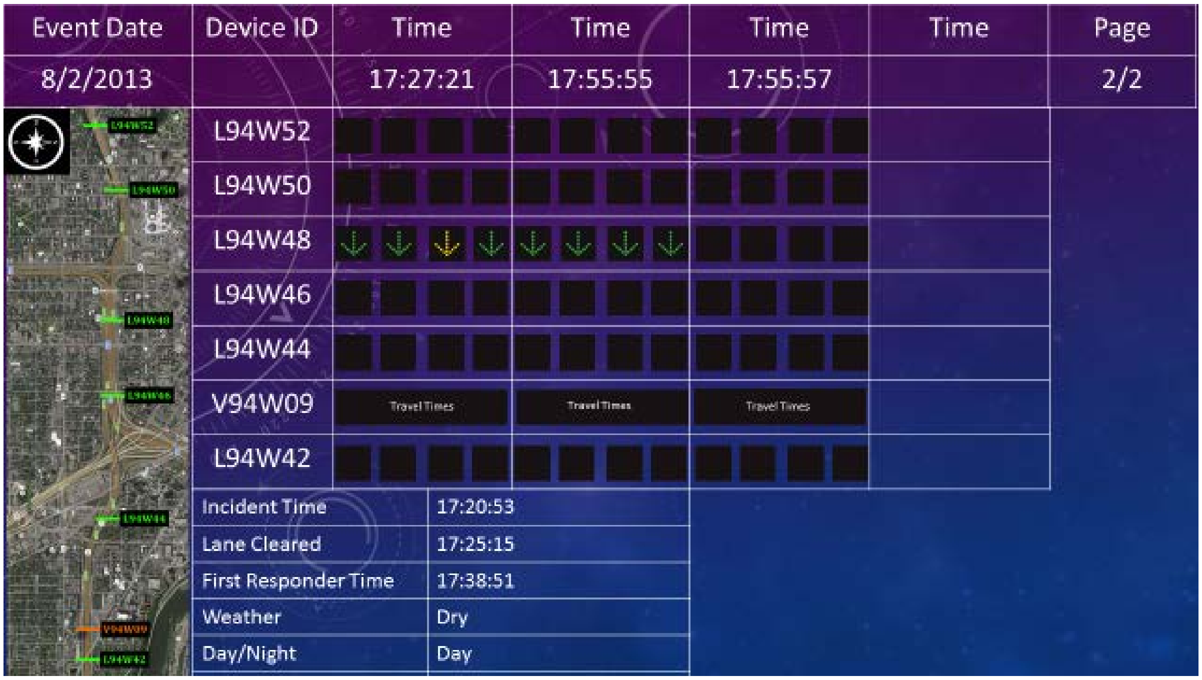


Figure 4-6. Event slide for 8/2/2013 continued.

The loop detector data show the shockwaves emanating from the crash. All three lanes experienced a severe reduction in volume and speed, first at station 1817 near Park Avenue, then at 11th Avenue a short time later. Once the ILCS system was activated, speeds and volumes began to return to pre-incident levels. Stable traffic patterns remained throughout the rest of the event.

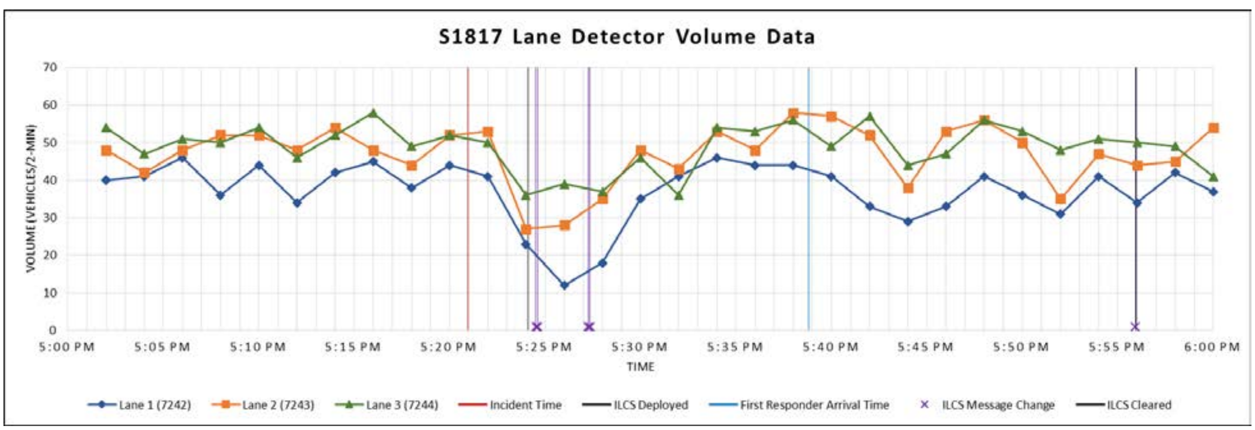


Figure 4-7. Volume data at Station 1817 (Park Avenue) - 8/2/2013.

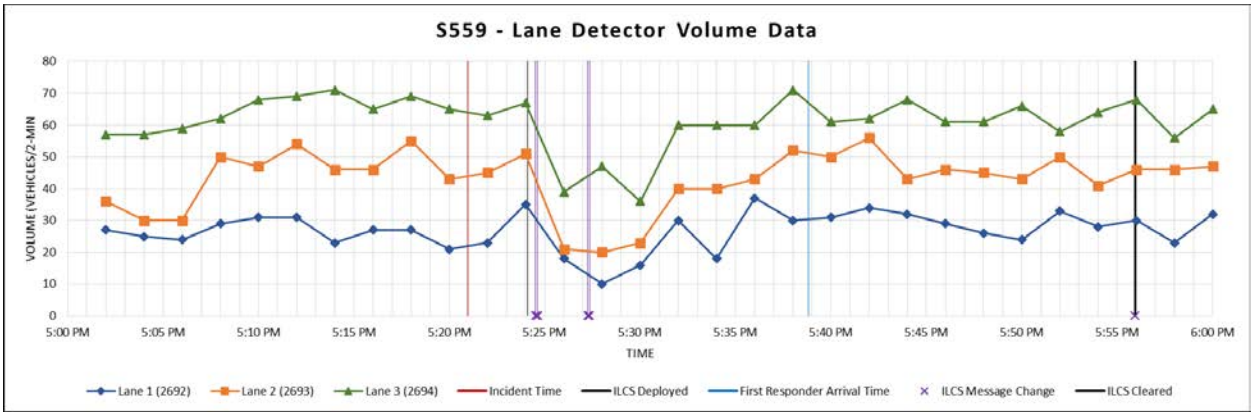


Figure 4-8. Volume data at Station 559 (upstream of 11th Avenue) - 8/2/2013.

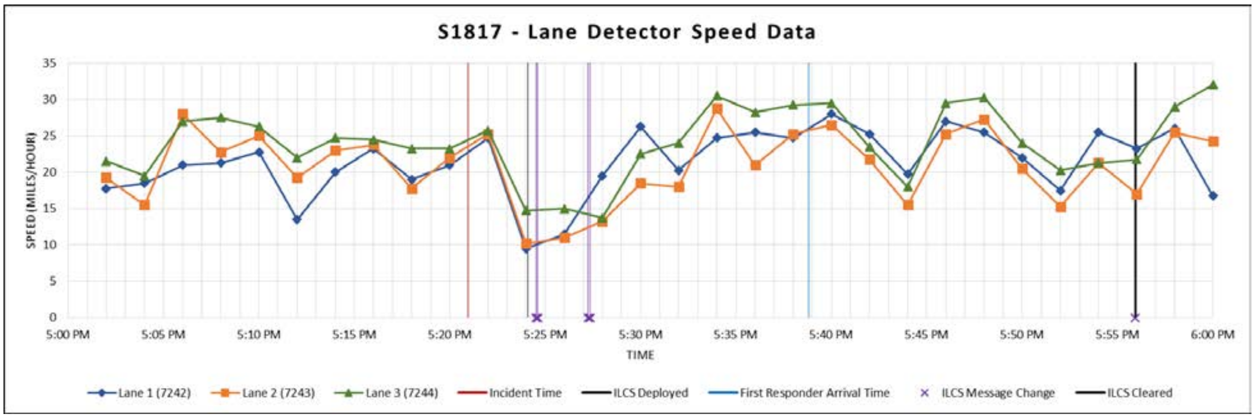


Figure 4-9. Speed data at Station 1817 (Park Avenue) - 8/2/2013.

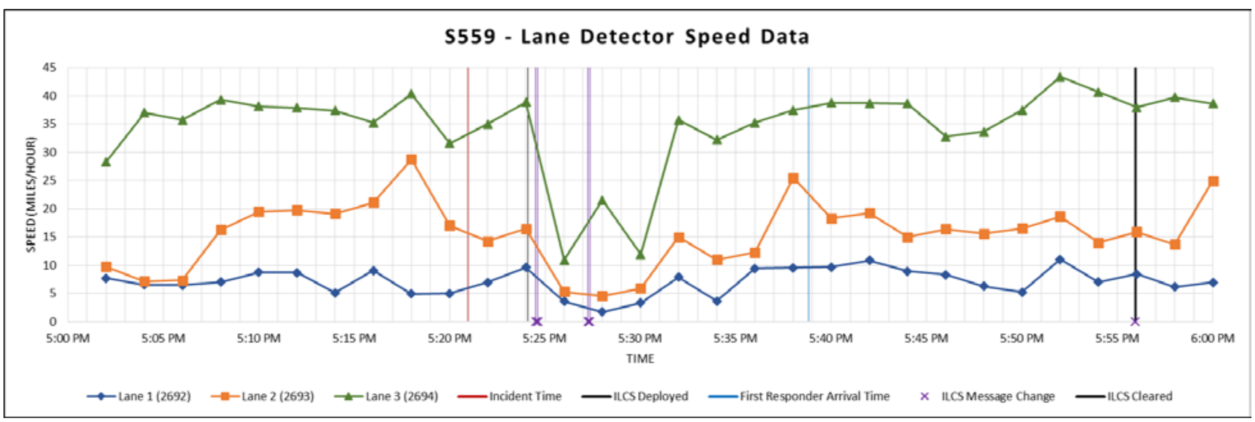


Figure 4-10. Speed data at Station 559 (upstream of 11th Avenue) - 8/2/2013.

Lane changes along the corridor prior to the incident exhibited the normal pattern for the region: significant lane changes into and out of lane one occurred at the merge point just west of 11th Avenue and sparse lane changes throughout the remaining corridor. The incident itself can be clearly seen with a pattern of exiting and re-entering lane changes near Portland Avenue. The activation of the ILCS appeared to induce exiting lane changes throughout the space between 11th Avenue and Portland in anticipation of passing the incident area.

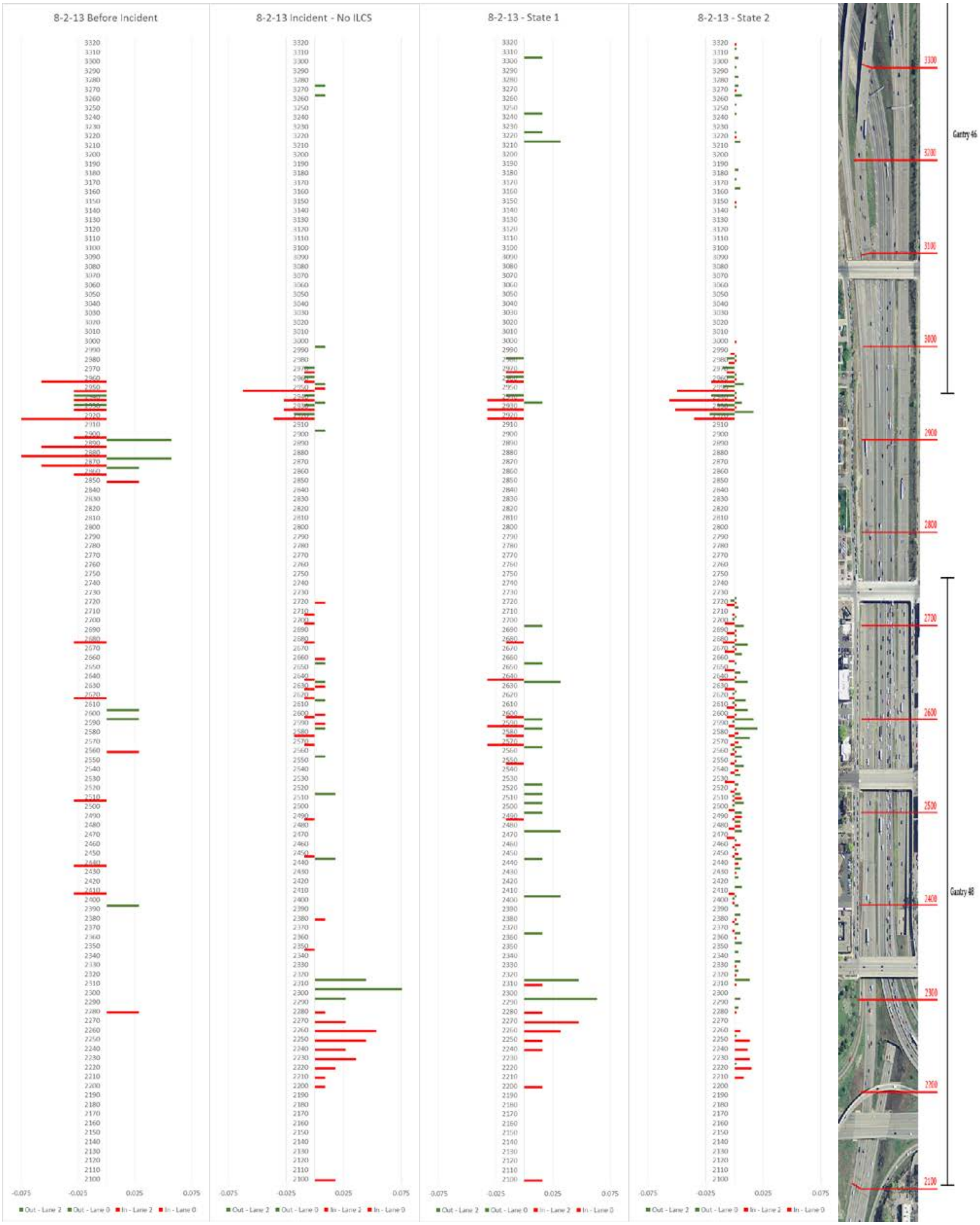


Figure 4-11. Lane changes by state for 8/2/2013.

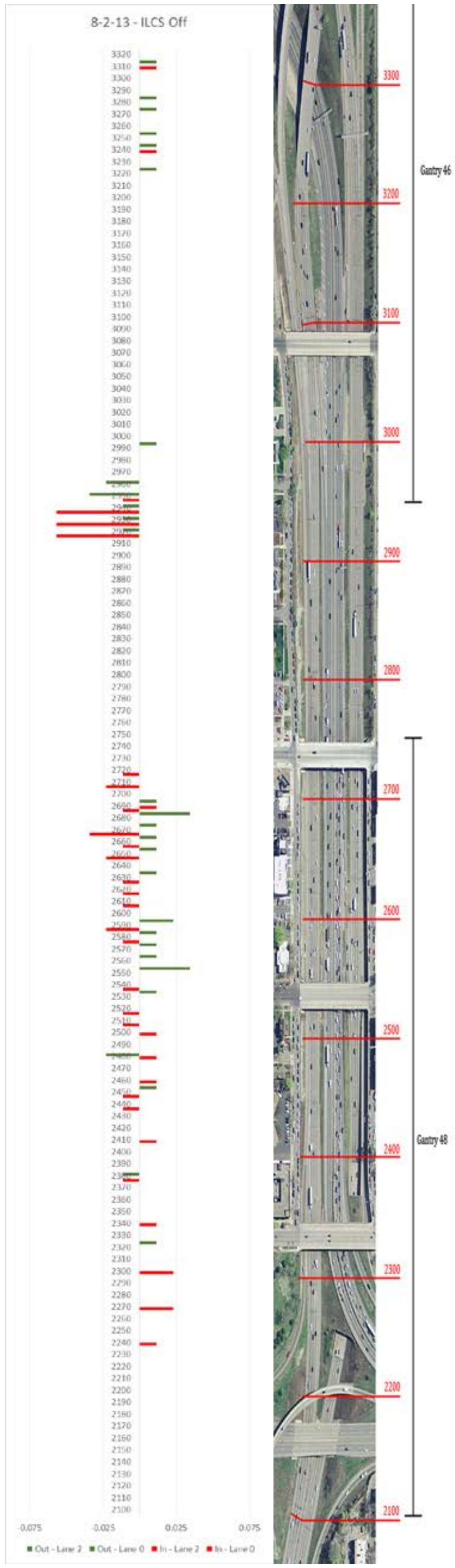


Figure 4-12. Lane changes by state for 8/2/2013 continued.

4.2.3 Sample Event 3: 6/21/2013 12:22:26 – 13:34:46

This event was chosen to portray a more severe event which features Lane Closed messages and multiple message changes. This event is a significant crash event located around the Portland Avenue Bridge, with multiple vehicles blocking the right lane and shoulder. A first, smaller event occurred at roughly 12:03, while a second larger event occurred 13 minutes later immediately adjacent to the other vehicles already on the shoulder. This secondary crash was the target of the ILCS system messages.

Once the incident was observed by RTMC operators, a crash message was put on the DMS at Riverside Avenue. Lane Closed indicators were put over lane one at both gantry 48 and 46, and an LCA sign was put further upstream at gantry 44. These remained for roughly 35 minutes. At that time, the Lane Closed indications were replaced with Use Caution, although the LCA and DMS messages were unchanged. A final state was deployed at 13:19 which removed the LCA from gantry 44. The Use Caution and DMS messages remained until the conclusion of the event at roughly 13:34.

Figure 4-13. Event slide for 6/21/2013.

Figure 4-14. Event slide for 6/21/2013 continued.

Figure 4-15. Event slide for 6/21/2013 continued.

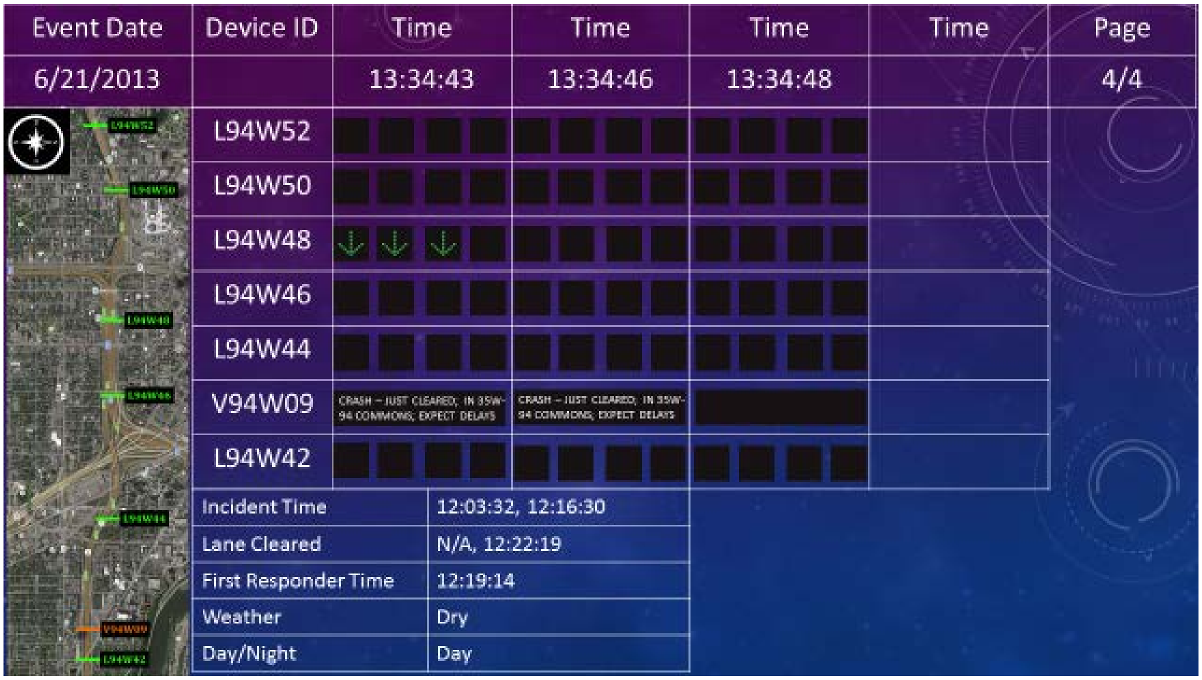


Figure 4-16. Event slide for 6/21/2013 continued.

The loop detector data along the corridor captured the propagation of queues upstream of the incident. Although the first crash at 12:03 produced a small decrease in speeds for lane one at Station 1817, conditions upstream were unaffected. The secondary crash at 12:16 produced a much larger and sharper decrease in speed and volume for both lane one and two. A recovery in speed for both lanes can be noted after the activation of the ILCS and the clearing of lane one.

As the congestion wave moved upstream, speeds and volumes decreased at Station 559 at roughly 12:22 and station S561 at roughly 12:25. Once the congestion reached each station, speeds remained roughly stable until much later within the incident.

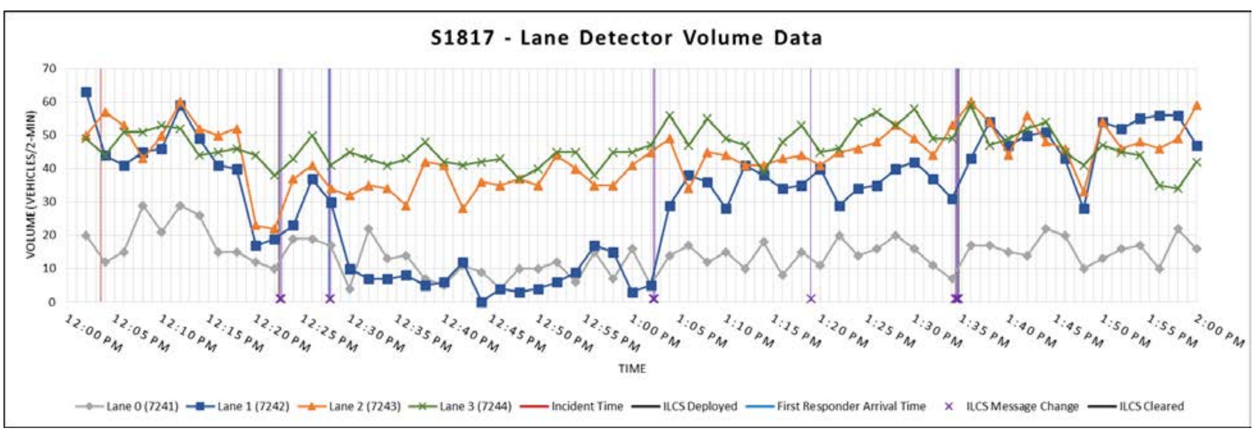


Figure 4-17. Volume data at Station 1817 (Park Avenue) - 6/21/2013.

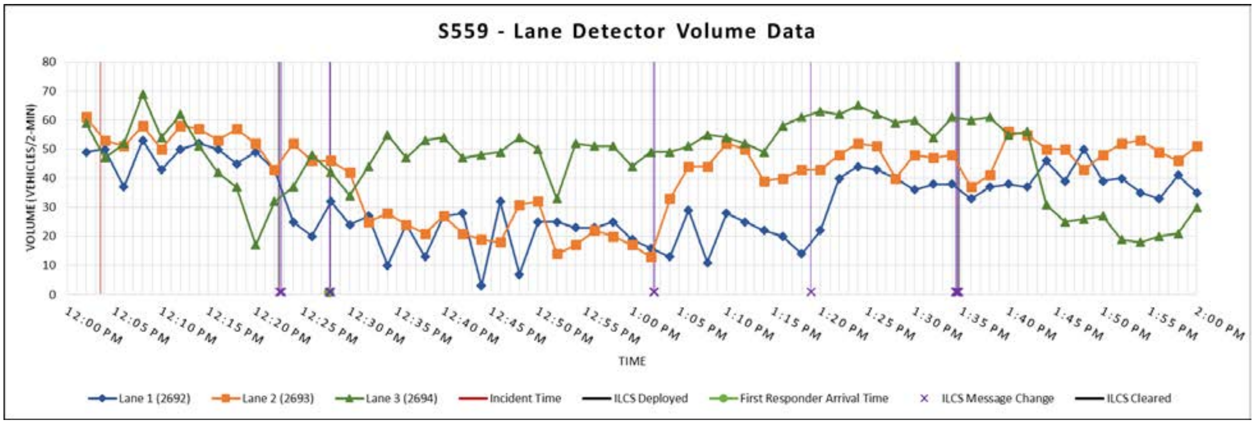


Figure 4-18. Volume data at Station 559 (upstream of 11th Avenue) - 6/21/2013.

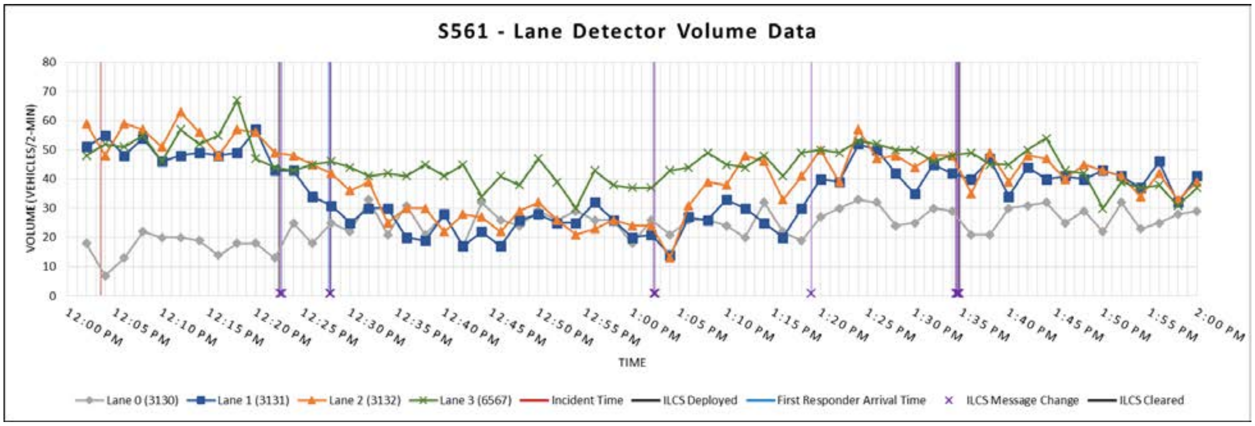


Figure 4-19. Volume data at Station 561 (Cedar Avenue) - 6/21/2013.

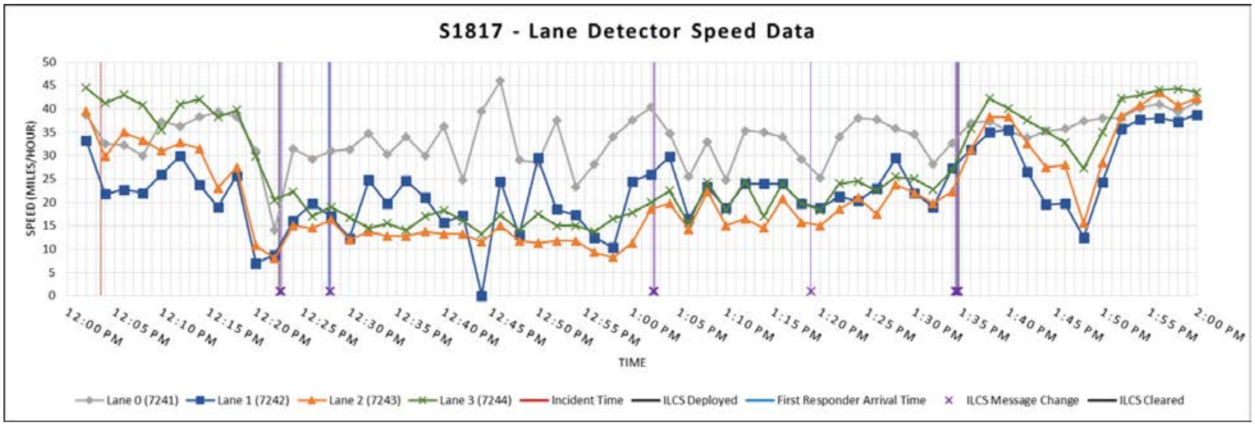


Figure 4-20. Speed data at Station 1817 (Park Avenue) - 6/21/2013.

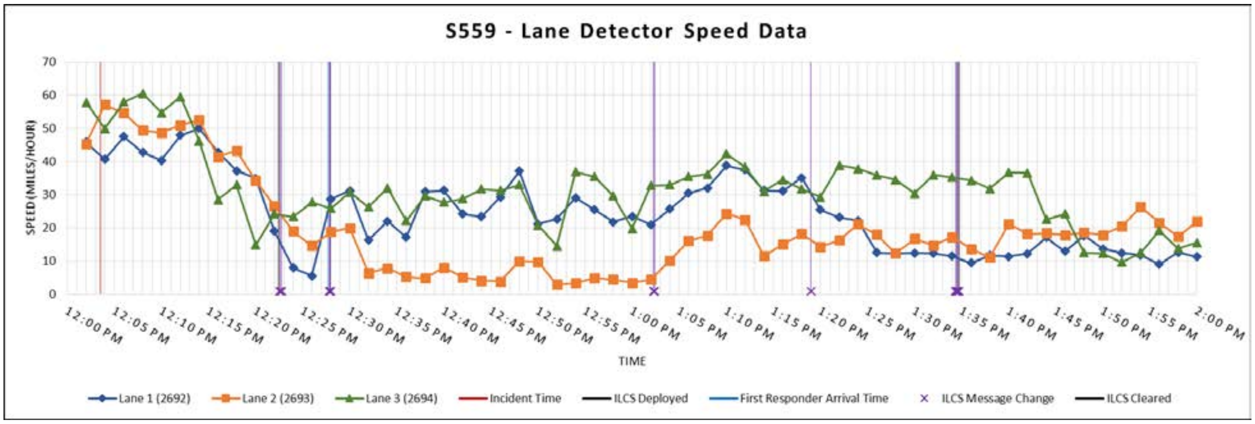


Figure 4-21. Speed data at Station 559 (upstream of 11th Avenue) - 6/21/2013.

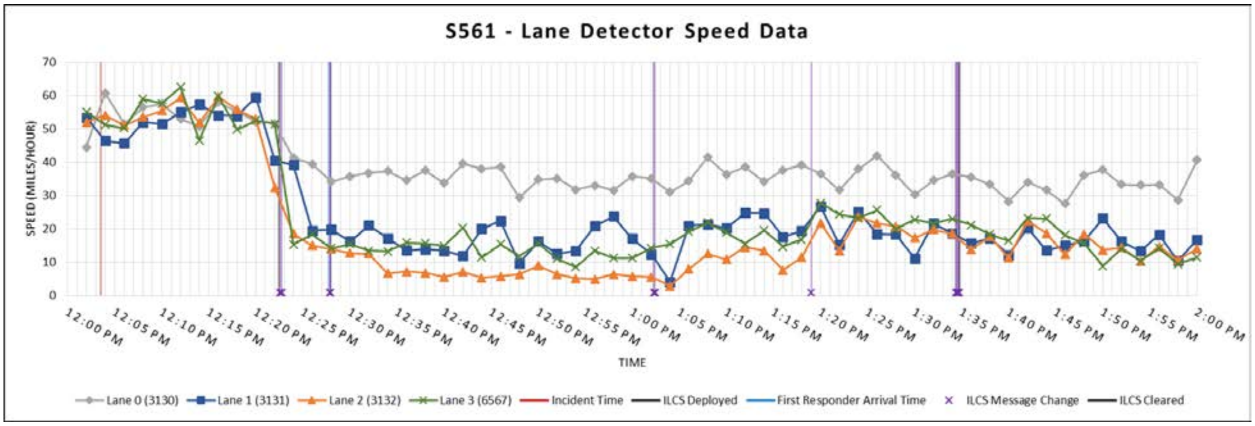


Figure 4-22. Speed data at Station 561 (Cedar Avenue) - 6/21/2013.

The lane changes for this incident clearly show the location of the crash prior to the activation of the ILCS. Once the signs were deployed, strong positive lane changes were observed, especially just upstream of gantry 46 (the first sign showing a Lane Closed message), with a more mixed effect around gantry 48. The response at the LCA sign at gantry 44 is, like gantry 48, mixed with lane changes both in and out of lane one. This suggests that encountering the Lane Closed sign is a strong signal to drivers to depart the lane.

Throughout the other states, similar positive effects can be observed near gantries 46 and 48, although their impact is diminished after the Lane Closed signs are replaced with Use Caution.

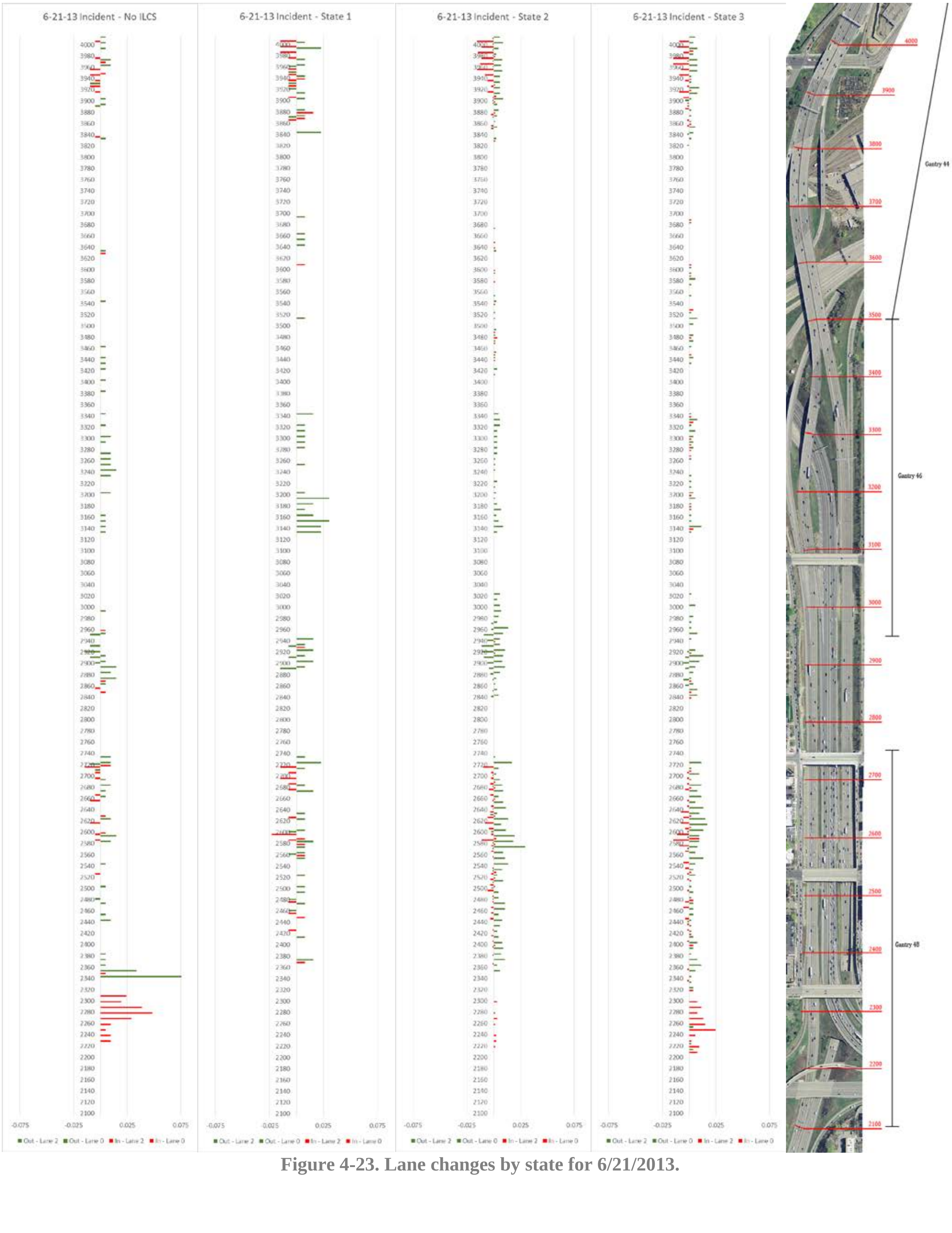


Figure 4-23. Lane changes by state for 6/21/2013.

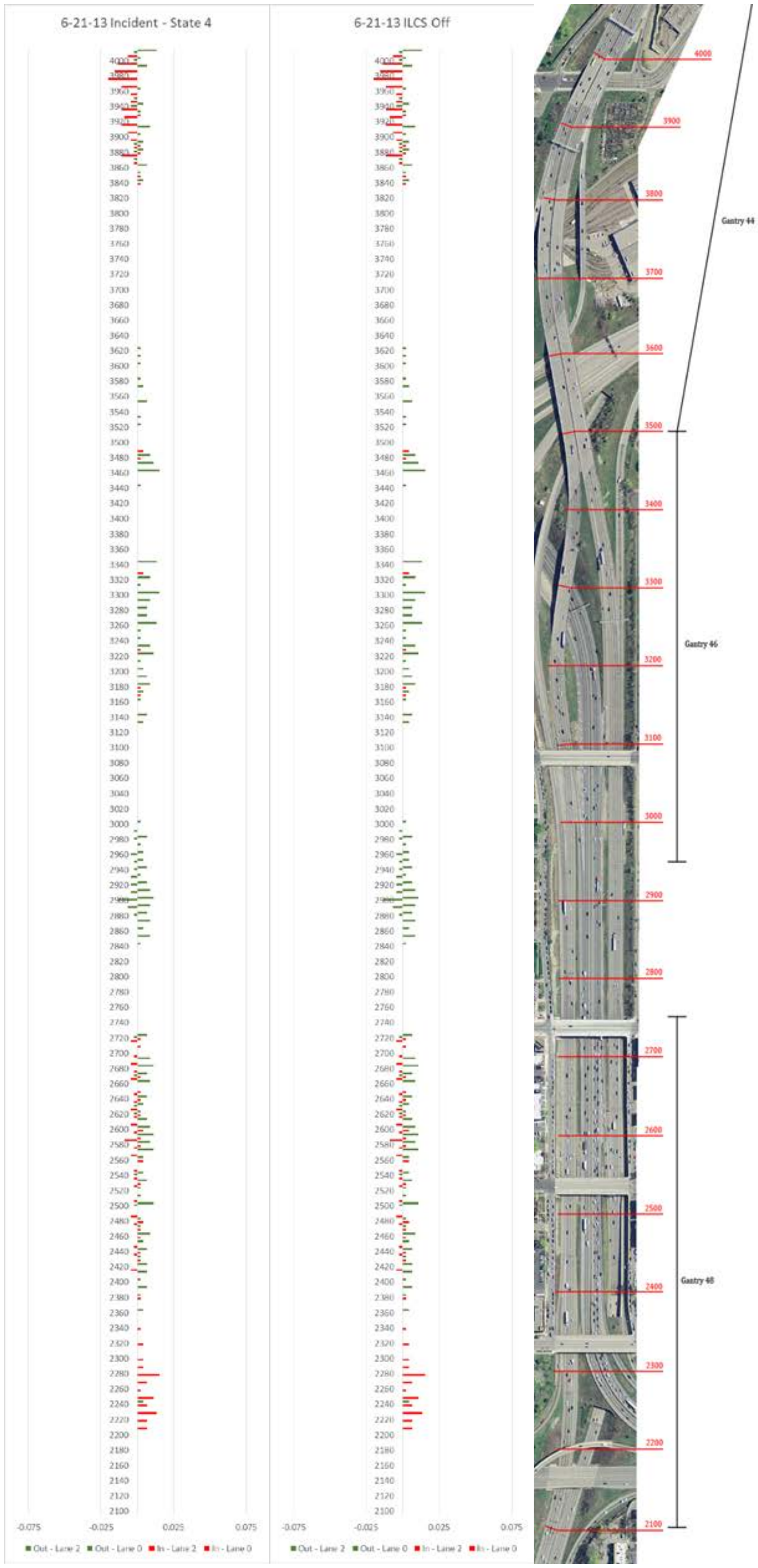


Figure 4-24. Lane changes by state for 6/21/2013 continued.

4.2.4 Sample Event 4: 8/21/2013 12:33:09 – 13:22:44

This event was included because it is the most severe one in the set of events. This incident involved a significant crash on the right lane at the High Crash Location. The right lane was blocked by an incident vehicle for a significant duration. As such, the ILCS displayed Lane Closed at Park Avenue and a Merge at 11th Avenue. The Merge Left was replaced with a LCA after several minutes. First responders arrived to control lane one at roughly 12:37, and were joined by several large firetruck/tow truck vehicles near 12:50. At that time, those vehicles blocked lane two and the ILCS was updated to show lane closure for both lanes. The corridor was reduced to one lane for roughly 15 minutes until sufficient clearance was given so that the middle lane could reopen. Another single-lane closure of significant duration took place and the vehicles blocking lane one were finally cleared at the close of the event. During this second single-lane closure period, a third gantry was activated with a Merge Left to begin pushing vehicles out of lane one at Cedar Avenue. The ILCS was deactivated for roughly four minutes prior to the final departure of all incident vehicles from the right shoulder under Portland Avenue.

Figure 4-25. Event slide for 8/21/2013.

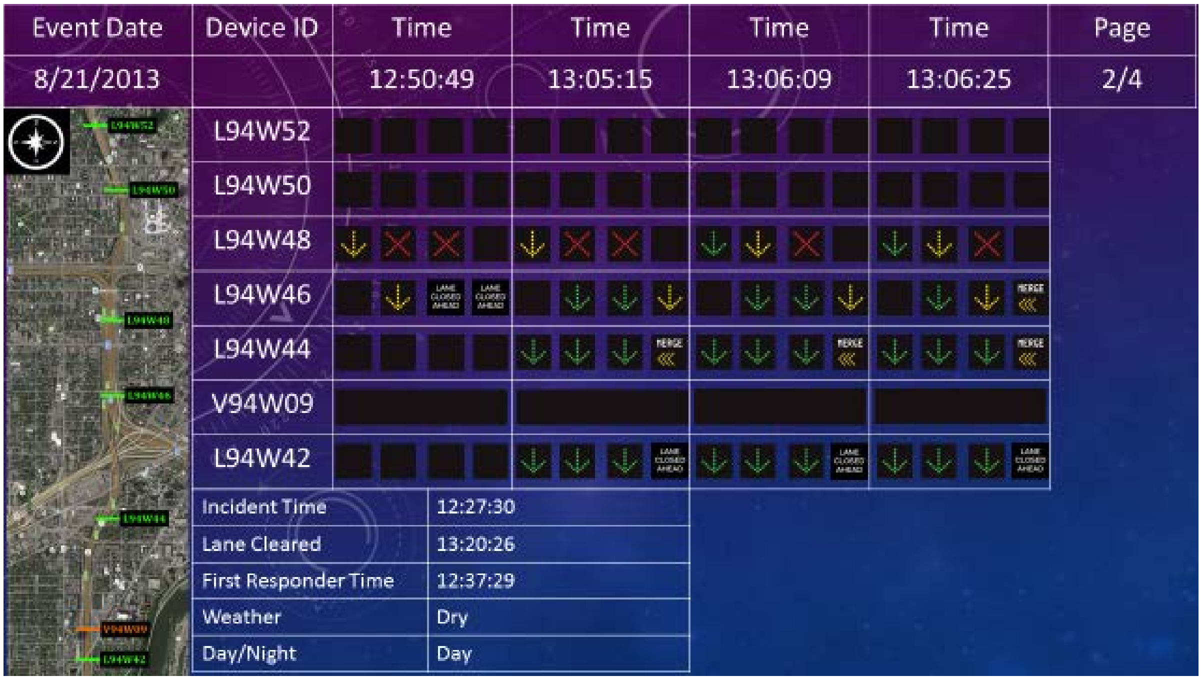


Figure 4-26. Event slide for 8/21/2013 continued.

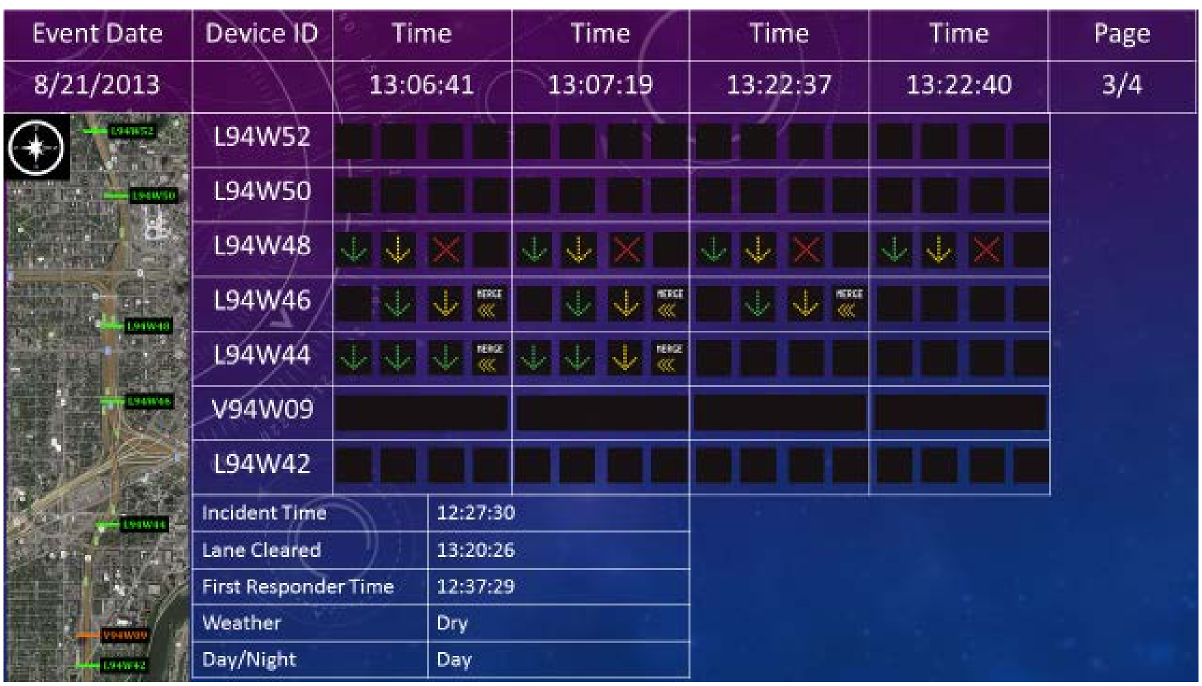


Figure 4-27. Event slide for 8/21/2013 continued.

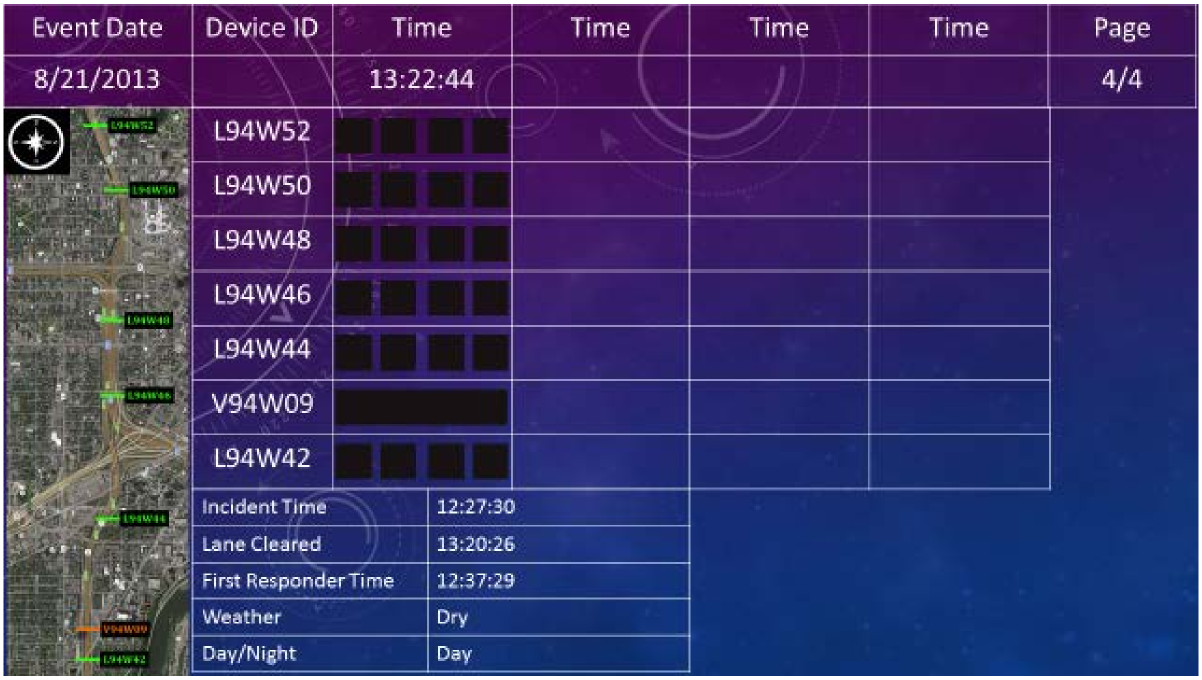


Figure 4-28. Event slide for 8/21/2013 continued.

At the crash location, volumes in lane one dropped precipitously, and speeds across all lanes fell to roughly 10 MPH for the entire duration of the event. Further upstream, a similar pattern occurred shortly thereafter. Speeds in lanes one and two were reduced to near zero at 11th Avenue, especially during the two-lane closure period.

The queues propagated upstream to Cedar Avenue at roughly the same time as the arrival of the first wave of first responder vehicles. A second slowdown occurred with the two-lane closure condition, with speeds dropping to near zero just like at 11th Avenue. After the conclusion of the incident, speeds and volumes slowly recovered at all locations, but did not immediately return to pre-incident levels.

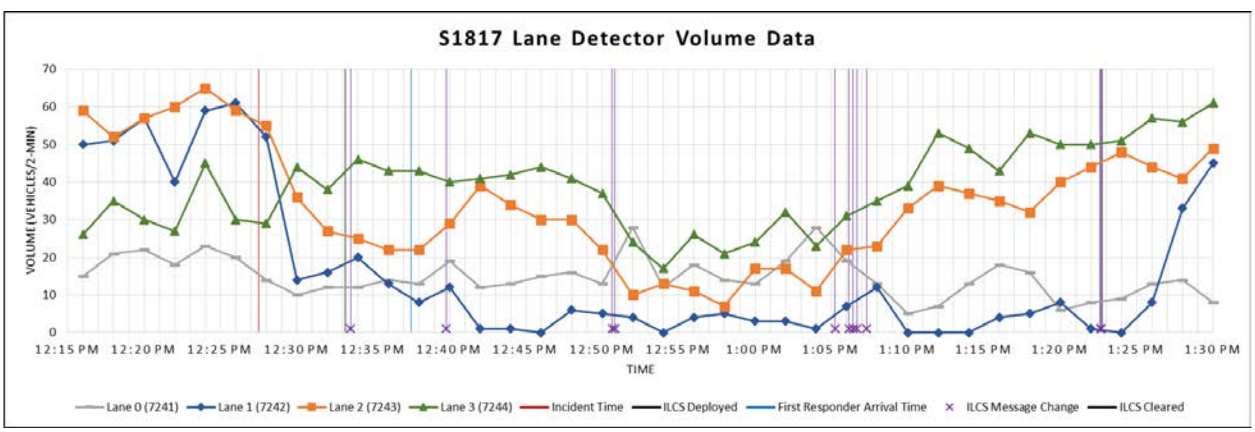


Figure 4-29. Volume data at Station 1817 (Park Avenue) - 8/21/2013.

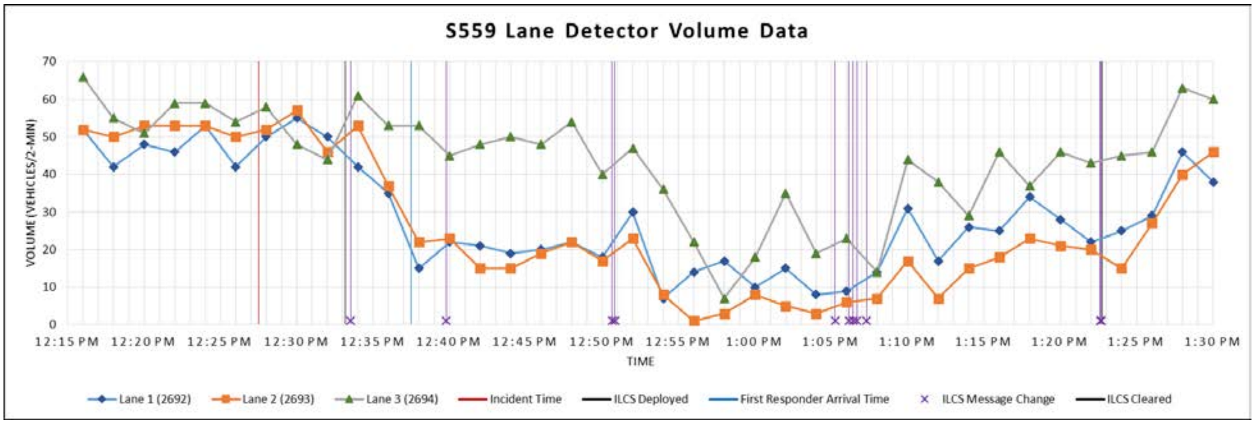


Figure 4-30. Volume data at Station 559 (upstream of 11th Avenue) - 8/21/2013.

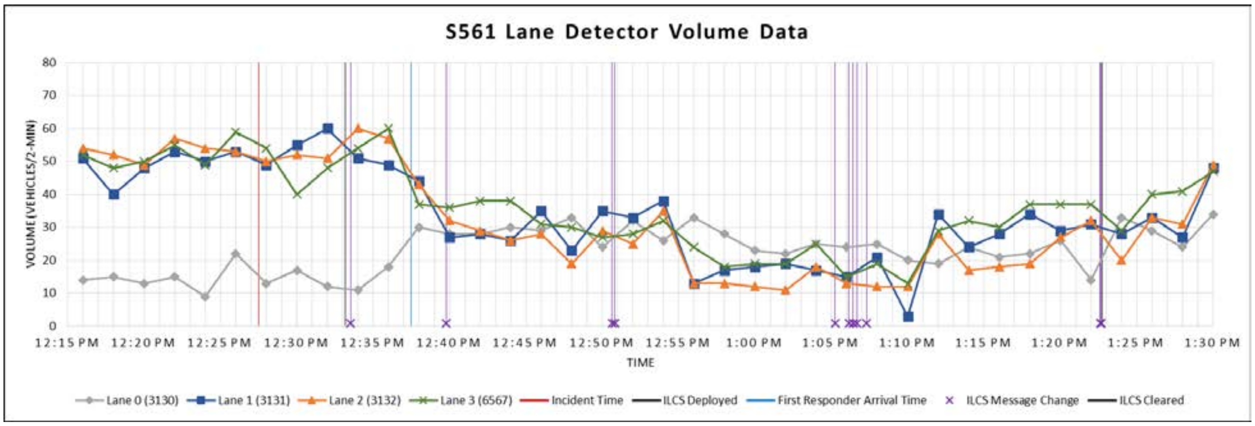


Figure 4-31. Volume data at Station 561 (Cedar Avenue) - 8/21/2013.

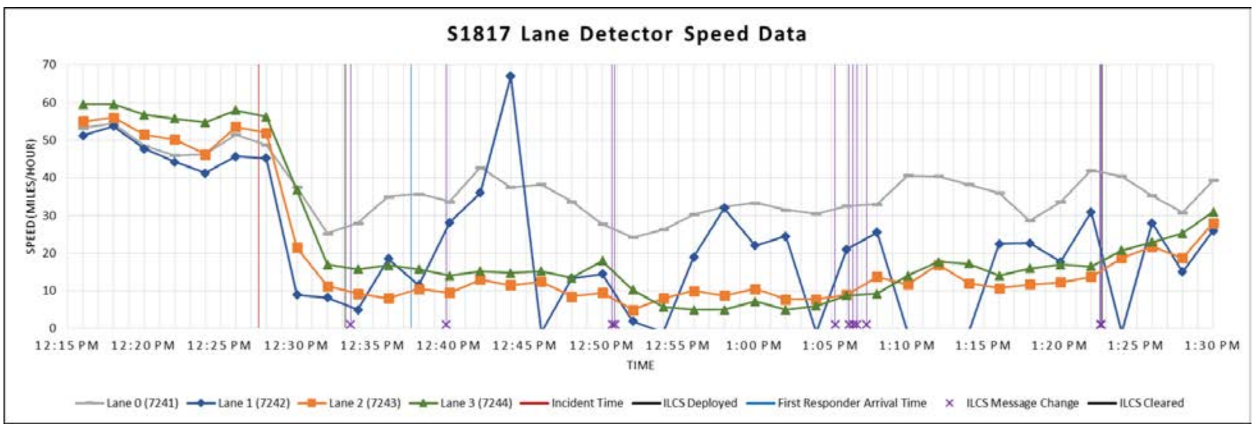


Figure 4-32. Speed data at Station1817 (Park Avenue) - 8/21/2013.

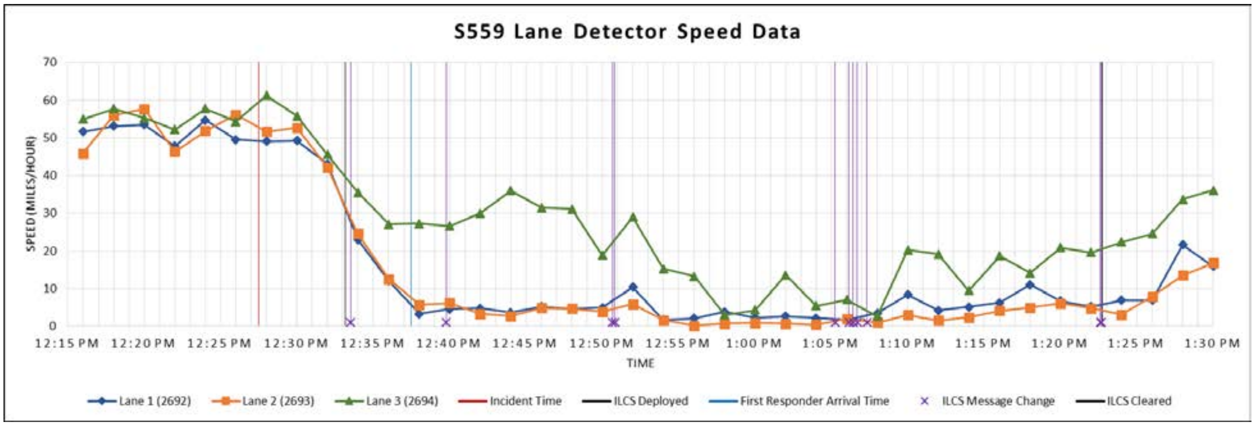


Figure 4-33. Speed data at Station 559 (upstream of 11th Avenue) - 8/21/2013.

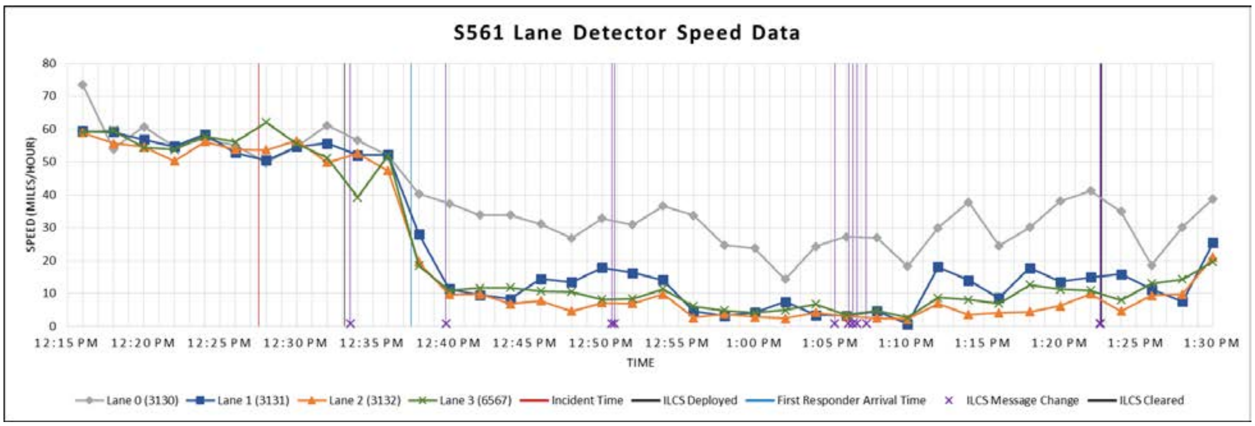


Figure 4-34. Speed data at Station 561 (Cedar Avenue) - 8/21/2013.

Within each state of the ILCS, some positive impacts can be seen. An increase in lane 1 to lane 2 lane changes can be seen in State 1 near marker 3200 (just upstream of 11th Avenue). This pattern continues through states 2, 3, and 5. Further downstream, positive lane changes are shown just upstream of the event, although these may have been due to either the presence of the ILCS or the presence of first responder vehicles. A signal showing the exact location of the incident can be seen at the far-downstream end of the corridor with vehicles leaving and re-entering lane one near marker 2300 (just downstream of Portland Avenue).

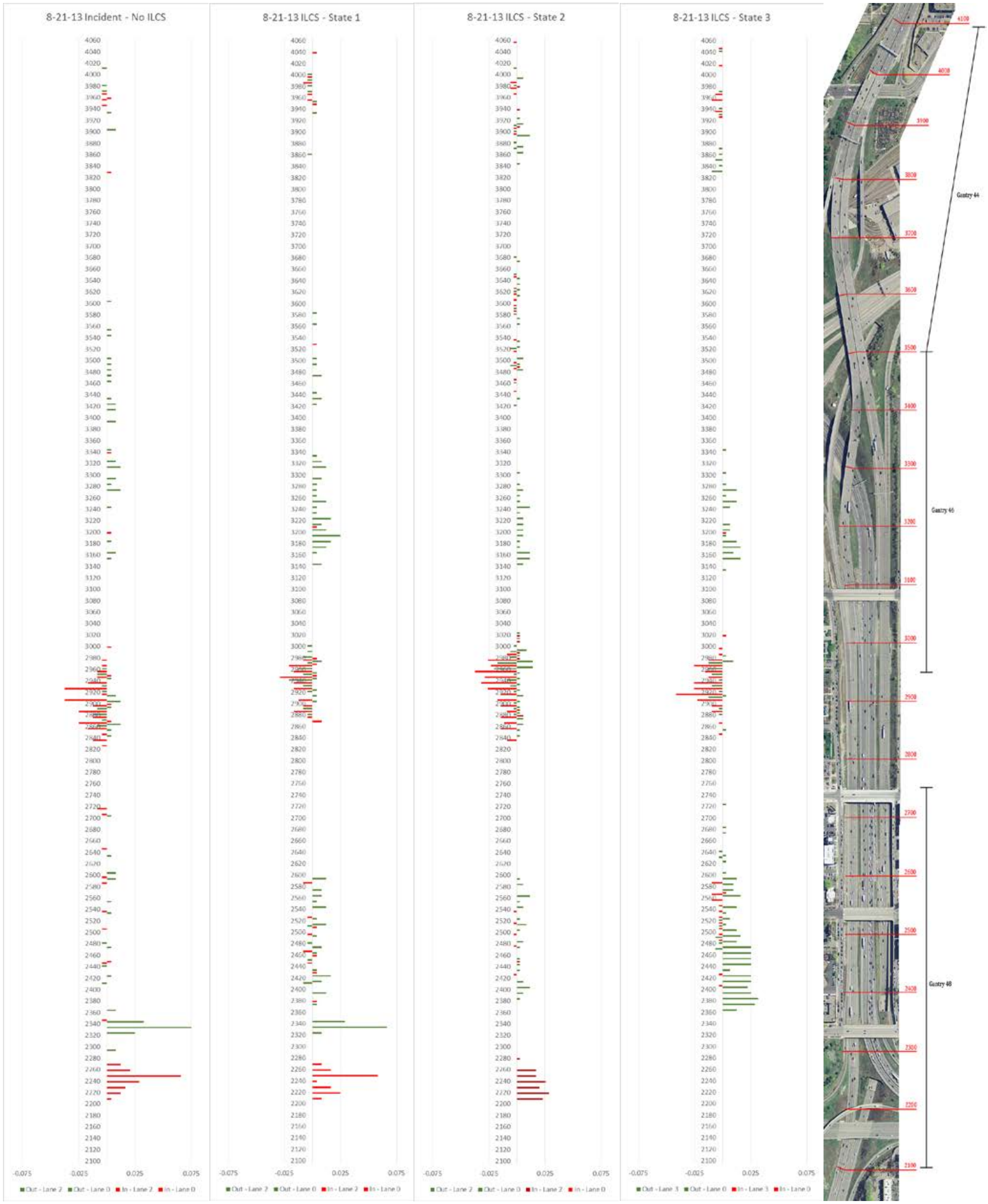


Figure 4-35. Lane changes by state for 8/21/2013.

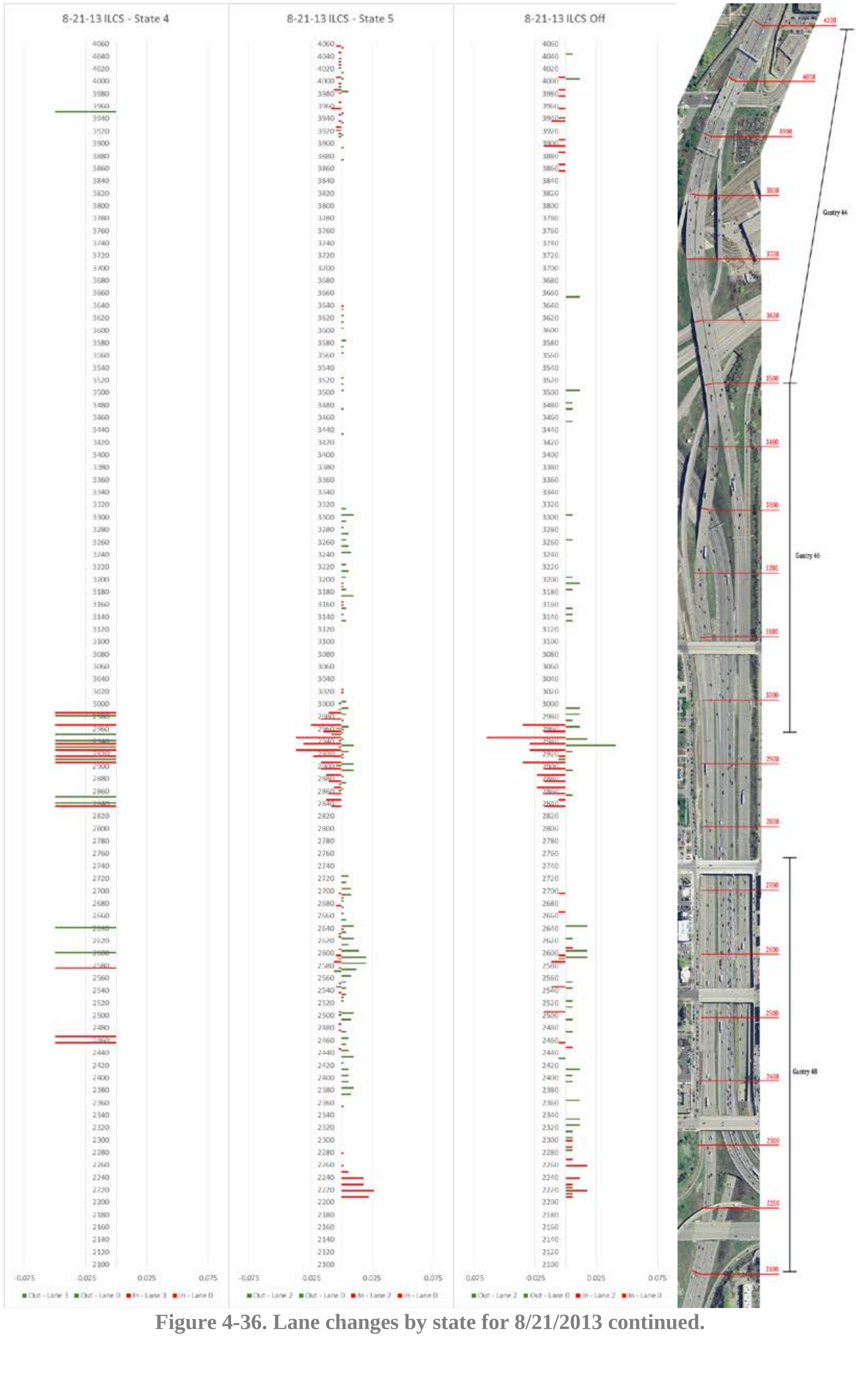


Figure 4-36. Lane changes by state for 8/21/2013 continued.

CHAPTER 5: MULTIVARIABLE REGRESSION MODELING

In addition to examining the data indicated above, a methodology was developed to model the impact of a variety of factors related to the ILCS system. A series of multi-variable linear regression models were created to measure the relative impacts of a series of sign configurations, as well as the impact of crash-related messages displayed on the dynamic message signs (DMS) located at Riverside Avenue (upstream of the corridor of interest) and the presence of the first responder vehicles (either police vehicles or FIRST trucks) at the site of the incident. This section describes the method used to prepare the data for modeling and the process of generating the regression model. The following chapter includes each hypothesis scenario which was examined and tested.

5.1 Data Compilation

In order to appropriately generate data points for modeling, a database was created to combine the ILCS activation logs, loop detector data, and lane changes observed from video. Each of these was loaded into individual tables. The loop data was imported as two-minute flow, density, and speed organized by detector ID. The individual lane changes which were collected from the video data were grouped into two-minute counts by distance along the corridor to coincide with the loop detector data date-time format.

The ILCS activation data was included as part of an event table. Each event was broken into two-minute intervals to correspond with the loop and lane change data. For each two minute period, each gantry was given a State ID and Configuration ID. State ID was a unique ID assigned based on the states identified from the ILCS configuration data. For example, the 2/7/2013 event included three states: pre-ILCS, ILCS deployed, post-ILCS. Each of these time periods was assigned an ID.

The Configuration ID assigned to each two-minute interval described the status of each gantry's signs. All the unique states which were assigned State IDs (as above) were grouped according to two parameters: what sign type was dominant at the gantry, and what 'number' the gantry was as part of the corridor. For example, the 3/15/2013 (a) event includes gantries 44 and 46. Only one ILCS state was identified for the event, in which gantry 44 displayed an LCA message and gantry 46 displayed a merge chevron. Gantry 44 was the 'first' or most-upstream gantry in the event, and gantry 46 was the 'second' in the incident. For 'first' gantries, indicating an LCA message was coded as Configuration ID = 3. Gantry 46, on the other hand, was given a Configuration ID of 11 which means a 'second' gantry showing merge *and* having an upstream gantry showing LCA. If instead gantry 44 had shown a yellow arrow for Use Caution, gantry 46 would have been coded using a different Configuration ID.

Table 5-1. Data coding results for all events

					Sign Type Deployed						
Date	**Time**	**Event State**	**State ID**	**Gantry**	*Use Caution*	*Merge Right*	*Merge Left*	*Merge Both*	*L.C.A.*	*L.C.*	**Configuration ID**
1/29/2013	**11:07:39-11:22:12**	**1**	**1**	44	X						1
		2	**2**	44	X	-	X	-	-	-	2
2/7/2013	**16:11:35-16:31:41**	**1**	**3**	48	X	-	-	-	-	-	1
2/18/2013	**13:24:51-13:27:30**	**1**	**4**	48	-	-	-	X	-	-	11
				46	-	-	-	-	X	-	3
3/4/2013	**13:21:55-13:46:24**	**1**	**5**	48	-	-	-	-	X	-	3
3/15/2013	**15:28:19-15:48:43**	**1**	**6**	46	X	-	X	-	-	-	13
				44	-	-	-	-	X	-	3
3/15/2013	**18:30:48-19:02:44**	**1**	**7**	46	X	-	X	-	-	-	13
				44	-	-	-	-	X	-	3
		2	**8**	46	X	-	-	-	-	X	24
				44	X	-	X	-	-	-	13
				42	-	-	-	-	X	-	3
3/21/2013	**16:24:38-17:12:10**	**1**	**9**	44	X	-	-	-	-	-	1
4/5/2013	**18:57:14-19:03:50**	**1**	**10**	46	X	-	X	-	-	-	13
				44	-	-	-	-	X	-	3
5/1/2013	**16:32:25-16:43:46**	**1**	**11**	44	X	-	-	X	-	-	14
				42	X	-	-	-	X	-	4
		2	**12**	44	X	-	-	X	-	-	10
				42	XX	-	-	-	-	-	1
		3	**13**	44	X						8
				42	XX						1
5/2/2013	**18:45:35-19:30:58**	**1**	**14**	48	X	-	-	-	-	-	1
5/3/2013	**11:46:12-12:00:28**	**1**	**15**	46	X	X					2
5/22/2013	**18:31:25-19:13:57**	**1**	**16**	48	-	-	-	-	X	-	16
				46	X	-	-	-	-	-	1
		2	**17**	48	X						1
		3	**18**	48	-	-	-	-	X	-	3
5/24/2013	**17:40:35-17:47:23**	**1**	**19**	48	X	-	-	-	-	-	1
5/31/2013	**14:34:58-14:42:12**	**1**	**20**	46	X	-	-	-	-	-	1

Date	Time	Event State	State ID	Gantry	*Use Caution*	*Merge Right*	*Merge Left*	*Merge Both*	*L.C.A.*	*L.C.*	Configuration ID
					Sign Type Deployed						
6/21/2013	**12:22:26-13:34:46**	**1**	**21**	48	X	-	-	-	-	-	23
				46	X	-	-	-	-	-	9
				44	-	-	-	-	X	-	3
		2	**22**	48	X	-	-	-	-	X	25
				46	X	-	-	-	-	X	20
				44	-	-	-	-	X	-	3
		3	**23**	48	X	-	-	-	-	-	23
				46	X	-	-	-	-	-	9
				44	-	-	-	-	X	-	3
		4	**24**	48	X	-	-	-	-	-	8
				46	X	-	-	-	-	-	1
7/1/2013	**16:39:50-16:48:53**	**1**	**25**	48	X	X	-	-	-	-	13
				46	-	-	-	-	X	-	3
8/2/2013	**17:24:06-17:55:57**	**1**	**26**	48	-	-	X	-	-	-	11
				46	-	-	-	-	X	-	3
		2	**27**	48	X	-	-	-	-	-	1
8/12/2013	**15:46:03-15:56:29**	**1**	**28**	44	-	-	-	-	X	-	3
8/13/2013	**16:46:13-17:23:11**	**1**	**29**	46	X	-	-	-	-	-	1
8/14/2013	**18:47:09-19:12:12**	**1**	**30**	48	X	-	-	-	-	X	20
				46	-	-	-	-	X	-	3
8/21/2013	**12:33:09-13:22:44**	**1**	**31**	48	X	-	-	-	-	X	19
				46	X	-	X	-	-	-	2
		2	**32**	48	X	-	-	-	-	X	21
				46	X	-	-	-	X	-	4
		3	**33**	48	X	-	-	-	-	XX	22
				46	X	-	-	-	XX	-	6
		4	**34**	48	X	-	-	-	-	X	26
				46	X	-	X	-	-	-	12
				44	X	-	X	-	-	-	2
8/27/2013	**14:45:57-15:29:36**	**1**	**35**	44	X	-	-	-	-	-	1
		2	**36**	44	X	-	-	-	X	-	17

Date	Time	Event State	State ID	Gantry	*Use Caution*	*Merge Right*	*Merge Left*	*Merge Both*	*L.C.A.*	*L.C.*	Configuration ID
					Sign Type Deployed						
				42	XX					X	7
		3	**37**	44	X	-	-	-	X	-	4
		4	**38**	44	-	-	-	-	XX	-	5
9/5/2013	**13:45:37-13:56:28**	**1**	**39**	46	X	-	-	-	-	X	24
				44	XX	-	-	X	-	-	13
				42	-	-	-	-	X	-	3
		2	**40**	46	X	-	-	-	-	X	27
				44	-	-	XX	-	-	-	15
				42	-	-	-	-	XX	-	5
		3	**41**	46	X	-	-	-	-	-	8
				44	X	-	-	-	-	-	1
9/19/2013	**12:59:50-13:01:14**	**1**	**42**	48	X	-	-	-	-	-	1
9/24/2013	**17:10:20-17:42:48**	**1**	**43**	44	XX	-	-	X	-	-	13
				42	-	-	-	-	X	-	3
12/18/2013	**15:54:30-18:19:36**	**1**	**44**	48	XX	-	-	-	X	-	20
				46	-	-	-	-	X	-	3
		2	**45**	48	XX	-	-	-	X	-	4
12/27/2013	**14:28:03-15:30:40**	**1**	**46**	44	X	X	-	-	-	-	13
				42	-	-	-	-	X	-	3
12/31/2013	**10:59:47-11:06:51**	**1**	**47**	48	X	X	-	-	-	-	13
				46	-	-	-	-	X	-	3

By examining all states, a tree of Configuration IDs was constructed for one, two, and three gantry systems. No events within the set included more than three successive ILCS gantries.

The event table also included several other pieces of descriptive information. Both the target and adjacent lane numbers were included in order to query related loop detector and lane change data for each event. The presence of first responders was coded as a binary parameter and was only true for the gantry region in which the crash took place. These regions can be seen in the lane change figures in previous sections, and generally include a short distance upstream of each gantry where line-of-sight to the ILCS signs is possible and a larger region downstream of the signs. Similar to the first responder, a binary parameter was included to describe the status of the DMS at Riverside, with 0 indicating no message or a travel time advisory information and 1 indicating a crash-related message

In order to combine these three data sets, one final lookup table was included in the database describing which detector ids correspond to each lane at each gantry.

Using the four tables described above, a series of queries were created to relate the loop detector and lane change data to each event at the two-minute interval scale. However, to keep with independence assumptions within the linear model described below, data was grouped based on the following parameters: date and state describing which event and ILCS settings are active; gantry number and configuration which describe what specific sign layout and region are of importance; and target lane density.

This final parameter, target lane density, is *not* the same as the numerical density produced by the loop detectors. The target lane detector at each gantry region was evaluated and assigned a Target Density Category (TDC) parameter. This parameter broke the density spectrum into four regions: 0 to 20 vehicles per mile (TDC = 0), 20-30 vpm (TDC = 1), 30-42 vpm (TDC = 2), and densities above 42 vpm (TDC = 3). These conditions were roughly considered as ‘free flowing traffic’, ‘uncongested traffic’, ‘congested traffic’, and ‘stop-and-go conditions’, respectively. This parameter was used to control for non-linear lane change behavior relative to density.

The ultimate queries used within the database produce a single row entry for each gantry during each state of each event, with the option to also separate based on the presence of the first responder or the condition on the DMS. These queries were performed and filtered based on the Configuration ID in order to target specific sign layouts for model analysis.

This grouping procedure transforms the loop detector data into average measures across the grouped time periods. Thus Average Target Flow, Density, and Speed are produced, and similar measures for the adjacent lane. Lane changes were transformed into a ‘Lane Change Rate’ by the following formula:

$$Lane\ Change\ Rate = \frac{Average(Lane\ Change\ Count)}{Average(Target\ Lane\ Flow)} * 100 \qquad \text{Eq. 5-1}$$

5.2 Data Modeling in R

A statistical computing program was chosen in order to execute the statistical analysis. The program chosen for this project was R. R is a free software environment for statistical computing and graphics. R provides a wide variety of statistical (linear and nonlinear modelling, classical statistical tests, time series analysis, classification, etc.) and graphical techniques, and is highly extensible.

Within R, there are functions which can automatically model regression equations and generate estimates. The main tool used for this project is the Ordinary Least-Squares method of estimation. Ordinary Least-Squares (OLS) regression is a generalized linear modelling technique that may be used to model a single response (dependent) variable. The technique may be applied to single or multiple explanatory (independent) variables and also categorical explanatory variables that have been appropriately coded.

Using the *pairs()* function, a scatterplot of each of the quantitative variables can be plotted against one another to show the relationships between the variables. An example can be seen in Figure 5-1 below. This example shows the relationship between the square root of the Average Lane Change Rate, the Average Target Density, and the Average Target Speed. In the figure, reference A describes the relationship between target lane density and speed which is approximately linear. Reference B shows the relationship between the root of lane change rate and target lane speed which does not show an obvious direct relationship. Note that the scatterplots in the upper right portion of the figure are mirrors of the plots in the lower left.

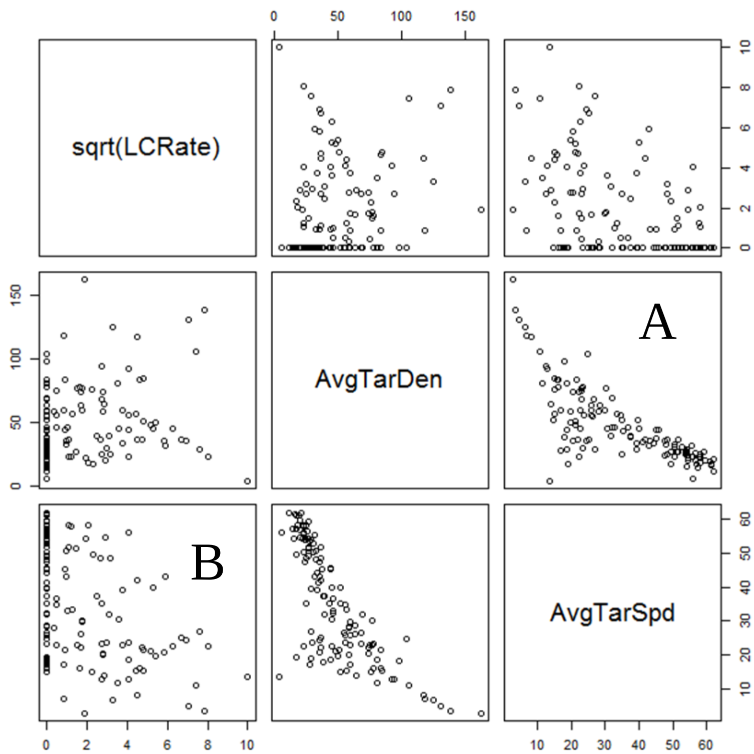


Figure 5-1. Sample output from pairs() function in R.

Using the predictors described above, a model can be fit using the *lm()* function. Once the model has been generated, assumptions related to the OLS model are checked and coefficient estimates from the regression can be displayed with the *summary()* function. An example of the regression output is shown in the Table 5-1.

Table 5-2. Sample output model parameters describing lane change rate.

Variables	Coefficient Estimates	Standard Error	t value	p-value	
Intercept	6.89	0.958	7.19	4.65e-11	***
Average Target Density	-0.0244	0.00917	-2.66	0.00873	**
Average Target Speed	-0.0993	0.0162	-6.13	9.91e-09	***

Multiple R-Squared	F-Statistic	Residual Std. Error
0.2734	24.27	1.954

Adjusted R-Squared	p-value	Degrees of Freedom
0.2621	1.134e-09	129

The estimated values for the coefficients, the standard error of the coefficients, the t value, and the p-value are given for each independent parameter. The p-values are assigned based on the results of the standard t test results. Each coefficient is marked with a 'significance' indicator, as described in Table 5-2 below.

Table 5-3. Significance levels and notation.

Significance Level	P-Value	Notation
90%	0.1	<no mark>
95%	0.05	.
99%	0.01	*
99.9%	0.001	**
100%	0	***

So it can be seen in Table 5-1 that both parameters of interest are significant, with average target density significant to 99.9% and average target speed 100% significant. Based on the coefficients, an increase in either of these parameters causes a decrease in the square root of lane change rate.

Overall the sample model has an R-Squared value of 0.2734 which means that the model captures approximately one-fourth of the data.

CHAPTER 6: RESULTS OF REGRESSION ANALYSIS

A series of hypotheses were created and tested, when sufficient data was available, using one of the multi-variable linear regressions. Each hypothesis and related test data will be described in this chapter. For those cases where sufficient data was available, the results and interpretation of the model are given. The research team felt prudent to include all hypothesis tested and untested and illustrate what is possible with more data collection or further experimentation.

Many models were examined while testing these hypotheses. As a result of these tests, it was found that a transformation of the Lane Change Rate parameter produced more robust results. Instead of using Lane Change Rate directly in the hypothesis tests described below, the square root of Lane Change Rate was used instead. By transforming the lane changes in this way, a stronger linear relationship is found with the independent parameters of each model.

There was a preliminary statistical analysis done with a sample size of 16 events. The results from that analysis were corroborated when the final analysis was completed. The increase in sample size from 16 events to 28 events did not change the results by much. This increases the confidence of the results in each of the final regression models.

6.1 Hypothesis 1

Hypothesis: A first gantry Lane Closed sign has a stronger effect on lane changes out of the incident lane than the other sign types.

The simplest cases to consider are those in which only one gantry along the corridor was activated. The first hypothesis considered was that a first gantry Lane Closed message has a stronger effect on lane changes than other sign types at a first gantry. Unfortunately, a Lane Closed configuration was rarely used as a first gantry configuration so there was insufficient data to test this hypothesis.

6.2 Hypothesis 2

Hypothesis: A first gantry ‘strong’ signal (i.e. Merge or Lane Closed Ahead) increases the rate of lane changes out of the incident lane as compared to a first gantry Use Caution signal or no ILCS.

The second hypothesis grouped several messages into a ‘strong message’ category in order to compare them against ‘weak messages’. In this case, Merge and Lane Closed Ahead messages were considered ‘strong’ while Use Caution was considered ‘weak’. The combination of Merge and LCA occurred more often than the Lane Closed configuration, so there was sufficient data available to test this hypothesis.

For this model's dataset, all of the 1st gantry states where a Use Caution, Merge (left, right, both), and Lane Closed Ahead were extracted from the database. In the dataset, the ILCS message configurations were sorted as a categorical variable where the Use Caution signal is one category and the 'strong' signals (Merge or Lane Closed Ahead) were combined to be a second category. The data when the ILCS was not active was also included in this dataset and was used as a base condition against which to compare the other configurations.

The response variable was the square root of the Average Lane Change Rate which was taken to give the model a better (more linear) fit, as described above. The predictors included in the first model were the Average Target Lane Density, the Average Target Lane Speed, the Average Adjacent Lane Density, and the Average Adjacent Lane Speed. Note that the Average Lane Change Rate is influenced deterministically by the Target Lane Flow, so including Flow in the linear model severely skewing the results and thus was excluded from the generated models.

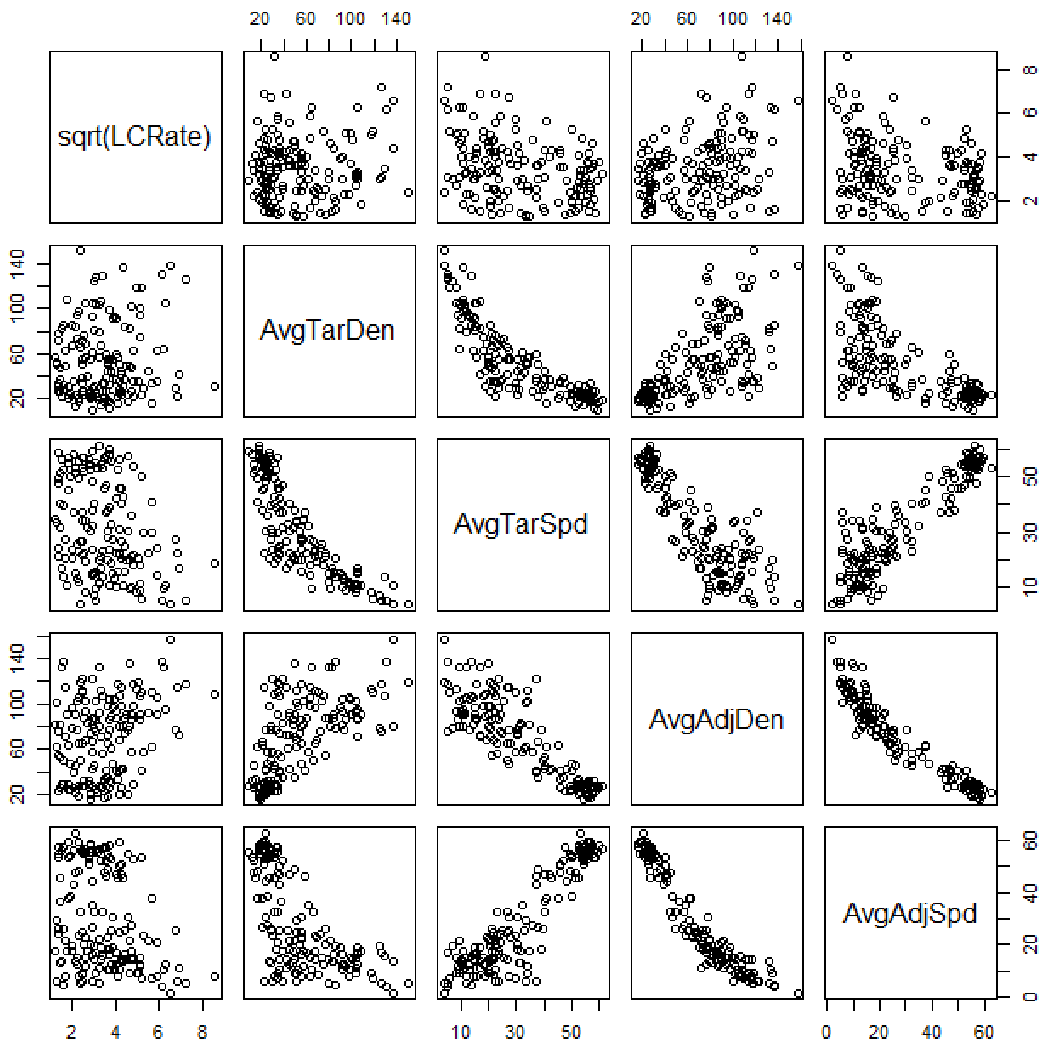


Figure 6-1. Scatterplot for variables in Hypothesis 2 model.

The scatterplots show that there is some multicollinearity in the model, which was expected. The densities and speeds in the target and adjacent lanes are related to one another (via the fundamental relationship). The predictors do seem to show a relationship with the response variable, so the OLS model assumptions were checked. None of the assumptions were violated, so the output of the model was fit and the estimates were generated.

Table 6-1. Model parameters describing lane change rate for Hypothesis 2.

Variables	Coefficient Estimates	Standard Error	t value	p-value	
Intercept	4.97	1.15	4.336	2.67e-05	***
Average Target Density	-0.0282	0.0056	-4.994	1.64e-06	***
Average Target Speed	-0.1184	0.0192	-6.158	6.59e-09	***
Average Adjacent Density	0.0163	0.0086	1.907	0.058500	.
Average Adjacent Speed	0.0781	0.0203	3.849	0.000176	***
Use Caution Config.	0.52	0.2964	1.771	0.078561	.
Strong Message Config.	1.19	0.2496	4.763	4.50e-06	***

Multiple R-Squared	F-Statistic	Residual Std. Error
0.3666	14.28	1.155

Adjusted R-Squared	p-value	Degrees of Freedom
0.3409	8.447e-13	148

All the parameters used within this model are noted as significant with p-values close to zero. The results of the regression estimates support the hypothesis that the Strong Messages have a larger effect on lane changes than the Use Caution signal. The Strong Message coefficient is roughly 67% higher than the Use Caution coefficient, suggesting that the presence of a Strong Message caused almost 70% more positive lane changes than the Use Caution sign. These values are relative to the no-sign condition.

One unusual result to note from the output is that the coefficients for density on the target and adjacent lanes are working counterintuitively. It would be expected that an increase in the density of the target lane would induce vehicles to leave the lane, while a high density adjacent lane would reduce lane change likelihood. These are reversed in the model shown above.

One possible explanation for this is that the target flow which is being used to generate the lane change rate is not accurately capturing the condition of the lane. Along the corridor, the significant entrance volume from the I-35W/Hiawatha Avenue ramp causes a large number of lane changes around gantries 46 and 48. These could be skewing the results of the model

To test this possibility, a second model was run which only included events at gantry 44. Gantry 44 does not encompass a significant entrance or exit ramp; the ramp toward 5th Street is relatively low volume compared to the mainline.

Table 6-2. Model parameters describing lane change rate for Hypothesis 2 - Gantry 44 only.

Variables	Coefficient Estimates	Standard Error	t value	p-value	
Intercept	6.64	1.987	3.342	0.001531	**
Average Target Density	-0.0173	0.0136	-1.268	0.210368	
Average Target Speed	-0.0464	0.0481	-0.964	0.339448	
Average Adjacent Density	-0.0142	0.0152	-0.939	0.352065	
Average Adjacent Speed	-0.0166	0.0419	-0.396	0.693807	
Use Caution Config.	0.74	0.5165	1.435	0.157088	
Strong Message Config.	1.71	0.4289	3.980	0.000211	***

Multiple R-Squared	F-Statistic	Residual Std. Error
0.466	7.709	1.131

Adjusted R-Squared	p-value	Degrees of Freedom
0.4056	5.566e-06	53

By including only gantry 44, two notable things change within the model. First, the direction of both target and adjacent density match. Thus, when target lane or adjacent lane density increases, lane changes decrease. This is consistent with what is observed in the field. The target and adjacent lanes are not exactly independent; when the density on one lane increases, the density on all lanes is generally increased. This is confirmed by the significance of the two factors. Only the target lane shows a significance within the model, while the adjacent lane becomes secondary. As for the sign of the coefficient, when density is high and vehicles are in congested or stop-and-go conditions lane changes diminish since there is no advantage to changing lanes.

The second observation from this model is the strength of the ILCS messages. As with the previous model, the Strong Message group shows a larger coefficient than the Use Caution sign. The influence of these parameters on lane changes is increased greatly, and the significance of the Strong Messages is greatly increased over the Use Caution message. This tells us two important things about the operation of the ILCS: the signs, especially stronger messages, have a notable and important effect on driver behavior within the corridor, and the influence of the signs is not uniform across the corridor.

By focusing only on gantry 44 the influence of the ILCS system is clearest and other confounding factors are minimized. When examining gantries 46 and 48, the influence of the entrance volume is non-trivial, especially on the right lane which is the target lane in the majority of the events selected for this analysis. Thus, the influence of those two downstream gantries is diminished simply due to geometric and demand concerns. The placement of the ILCS messages within the corridor is of great importance in determining their impact on traffic behavior. One can hypothesize that a smaller number of ILCS appropriately placed can be more effective than a larger number of every-half mile ones.

6.3 Hypothesis 3

Hypothesis: The Riverside Avenue DMS used concurrently with messages at the ILCS gantries has an effect on the rate of lane changes downstream.

Sub hypothesis: The presence of the DMS eliminates the benefit from the ILCS.

This model was developed to consider the impact of displaying crash-related messages at the DMS at Riverside Avenue. The data used to generate the coefficients in Table 6-3 is the same as used for the first model of Hypothesis 2, but the data was also grouped based on the DMS message state. The DMS was coded as a binary variable with 0 indicating when the sign was either off or displaying generic travel time information and 1 indicating a crash-related message.

Table 6-3. Model parameters describing lane change rate for Hypothesis 3.

Variables	Coefficient Estimates	Standard Error	t value	p-value	
Intercept	5.7194	1.1349	5.040	1.29e-06	***
Average Target Density	-0.0339	0.0053	-6.434	1.49e-09	***
Average Target Speed	-0.1403	0.0185	-7.592	2.82e-12	***
Average Adjacent Density	0.0159	0.0084	1.892	0.0604	.
Average Adjacent Speed	0.0886	0.02	4.424	1.82e-05	***
Use Caution Config.	0.4779	0.3028	1.578	0.1166	
Strong Message Config.	1.2203	0.2565	4.757	4.49e-06	***
DMS Message Active	-0.0323	0.2808	-0.115	0.9085	

Multiple R-Squared	F-Statistic	Residual Std. Error
0.4137	15.53	1.19
Adjusted R-Squared	**p-value**	**Degrees of Freedom**
0.3871	2.657e-15	154

From this model, we can see that the presence of a crash-related DMS message has minimal additional effect on lane change rate. It should be noted that because the DMS is upstream of the MTO camera views, none of its individual effect on lane changing behavior is being captured.

The drivers who see the DMS and change lanes immediately (or before gantry 44) are not being quantified. Another reason could be that when drivers see the DMS they take that information into consideration, but do not act until they are closer to the incident. The Strong message or the Weak message configuration used concurrently with the DMS active upstream induces a higher lane change rate than without the DMS, so the DMS works well along with the ILCS. Therefore Hypothesis 3 is valid but sub hypothesis 3 is not supported by the observations. The model is still consistent with the findings for the ILCS messages from previous models, showing that the Strong Message configuration is indeed more impactful and significant than the Use Caution warning.

6.4 Hypothesis 4

Hypothesis: The presence of a first responder at a crash location has a positive impact on lane change rate.

Sub hypothesis: The presence of the first responder eliminates the benefit from the ILCS.

Similar to Hypothesis 3, the data underlying Hypothesis 2 was reformulated based on the presence of first responders. A simple binary value was added with 0 indicating no first responder on scene and 1 indicating the presence of a first responder (either a police vehicle or a FIRST truck). One important caveat for this data is that a first responder was coded as present only for the nearest gantry. Thus for a hypothetical incident involving gantries 48 and 46 and which included a first responder near a crash location at Portland Avenue, gantry 48 would have a first responder value of 1 while gantry 46 would be coded as 0 even if the first responder were on scene further downstream.

Table 6-4. Model parameters describing lane change rate for Hypothesis 4.

Variables	Coefficient Estimates	Standard Error	t value	p-value	
Intercept	4.287	1.1304	3.79	0.000209	***
Average Target Density	-0.0275	0.0052	-5.33	3.23e-07	***
Average Target Speed	-0.1241	0.0183	-6.77	2.22e-10	***
Average Adjacent Density	0.0214	0.0081	2.63	0.009246	**
Average Adjacent Speed	0.0917	0.0197	4.66	6.51e-06	***
Use Caution Config.	0.31	0.2915	1.06	0.288824	
Strong Message Config.	1.14	0.2459	4.62	7.68e-06	***
First Responder on Scene	0.78	0.2360	3.32	0.001115	**

Multiple R-Squared	F-Statistic	Residual Std. Error
0.419	16.9	1.214
Adjusted R-Squared	**p-value**	**Degrees of Freedom**
0.3942	< 2.2e-16	164

The results of this model are similar to those involving the DMS. The presence of a first responder has a positive impact on lane changes, and is much more significant than in the case of an upstream DMS. Importantly, the impact of the first responder is strong, but not as strong as a ‘strong’ ILCS message. The presence of a first responder does not overpower or can replace the ILCS information. Therefore, Hypothesis 4 is valid but sub hypothesis 4 is not supported by the observations.

6.5 Hypothesis 5

Hypothesis: A second gantry Lane Closed sign after a Lane Closed Ahead sign induces more lane changes than a second gantry Merge sign after a Lane Closed Ahead sign.

All preceding hypotheses were examining first gantries within larger ILCS events. The possibility of exploring multiple gantry systems and the impact of successive messages was considered. However, insufficient sample sizes were still an issue despite expanding the sample set. This hypothesis was the only second gantry one where the sample size was close to being large enough.

This model was developed to check the second gantry case where the first gantry is a Lane Closed Ahead sign and the second gantry is either a Lane Closed signal or a Merge Chevron.

Table 6-5. Model parameters describing lane change rate for Hypothesis 5.

Variables	Coefficient Estimates	Standard Error	t value	p-value	
Intercept	6.003	1.3847	4.335	2.89e-05	***
Average Target Density	-0.0476	0.0061	-7.804	1.73e-12	***
Average Target Speed	-0.1244	0.0202	-6.171	8.01e-09	***
Average Adjacent Density	0.0228	0.0091	2.493	0.01393	*
Average Adjacent Speed	0.0732	0.0216	3.396	0.00091	***
Merge After LCA Config.	1.49	0.3427	4.372	2.50e-05	***
Lane Closed After LCA Config.	0.67	0.4770	1.410	0.16097	

Multiple R-Squared	F-Statistic	Residual Std. Error
0.6241	35.98	1.258
Adjusted R-Squared	**p-value**	**Degrees of Freedom**
0.6068	< 2.2e-16	130

In this case, the hypothesis was rejected. A second gantry Lane Closed sign after a Lane Closed Ahead sign does not induce more lane changes that a second gantry Merge sign after a Lane Closed Ahead sign. This model indicates that a Merge chevron after a Lane Closed Ahead sign actually induces significantly more lane changes than a Lane Closed signal after a Lane Closed Ahead sign. A corollary to this observation is that having only one upstream sign indicating the presence of trouble downstream followed with more precise directions on what is the best way out would be a successful combination. The latter does not have to be an ILCS but it could be an arrow sign on a FIRST truck or something similar.

CHAPTER 7: CONCLUSIONS

This project investigated the use of ILCS based ATM for Incident Management on a heavily traveled urban freeway. The subject of the research was the ILCS system on I-94 westbound in downtown Minneapolis. This location was selected because of the frequency of capacity-reducing incidents occurring in this freeway segment. Such a frequent crash location was necessary because of the large number of possible strategies one can employ using this type of system. Although this research could have used a more traditional approach of testing/measuring the effect such a system has on overall congestion, such a quantification would have been rough at best given the stochastic nature of both incident conditions and response scenarios. Instead, this research aimed to evaluate and quantify the effect the system has on drivers, specifically on inducing/directing a desirable lane selection behavior. Thus the strength of various uses of the tool in managing traffic during incidents is explored instead of a general level of success in improving traffic. Such an approach provides better help to traffic operators, although it does leave somewhat unanswered the question of the overall benefit of using this particular system. To achieve this goal, the centerpiece of this research was the comparison and modeling of the lane change rates under different strategies. This was a difficult task because all lane changes in the target freeway section had to be detected and geolocated. A number of MTO undergraduate students spent hundreds of hours each on this daunting task.

The research followed two main thrusts. The first was a detailed analysis of 28 incident events selected among approximately 481 events on record between 2012 and 2013. Given the detailed nature of the analysis, the reduction of only 28 events was possible with the given project's budget although the information and methodology exists for further analysis. The second thrust was a statistical analysis testing a number of hypotheses prompted by questions proposed by the project TAP. Where the empirical analysis of each of the selected events offers a detailed deconstruction of the effect each particular scenario had on traffic and driver lane selection behavior, the statistical analysis tried to quantify and rank the different incident management alternatives. For brevity, the main project report contains a detailed description of four events while an appendix report has all events analyzed.

From both analysis thrusts, it can be concluded that the use of ILCS for incident management has a significant effect on driver behavior and specifically in prompting proper lane selection under capacity-reducing incidents. Although the ILCS was envisioned as a unified system of equidistant successive gantries, based on the observations made in this research, the inclusion of more than two gantries upstream of the incident in a response strategy is unnecessary since it does not seem to offer any additional benefit. This conclusion does not include the use of VSL three-quarters of a mile and farther upstream of the incident. An earlier research project showed that in the case of the advisory VSL used in Minnesota, they do not seem to be significantly affecting driving behavior. Therefore, using the two upstream ILCS for lane state information is much more effective, while farther upstream gantries can be displaying VSL since they cause no harm.

Another general observation bringing evidence against the equidistant placement of ILCS is that they seem to be greatly affected by the particular road geometry. For example, given the very specific nature of the I-94 westbound high crash area, in the case of the gantries on 11th Avenue and Park Avenue, they may be less effective than a single gantry on or just east of Chicago

Avenue. The gantry on 11th Avenue seems to have a weak operational effect because it misses all the traffic that enters from the combined 35W/Hiawatha ramp leaving them without warning until the Park Avenue gantry, which is considerably closer to the incident location and thus more quickly overrun by propagating queues. It could be considerably more effective and perhaps more economical to locate the ILCS based on historical crash locations rather than as a blanket system on a freeway corridor.

In terms of specific scenarios of ILCS use, this research showed that specific sign configurations induce more lane changes, than others. Specifically, the Use Caution sign has a relatively weak effect on lane changes especially in comparison to stronger messages like Merge, LCA and LC. Perhaps intuitively, the Merge chevron sign seems to be the strongest sign for inducing lane changes upstream of an incident. The research has also shown that the combination of LCA followed by a Merge chevron on successive gantries is most effective. During this research, it was not possible to observe/compare the strength of an ILCS Merge chevron against a FIRST truck mounted arrow board and by extension the effectiveness of a combination single ILCS and FIRST unit.

The analysis as well as the empirical evidence show that the visual presence of first responders like FIRST and State Patrol vehicles has an observable positive effect on lane change behavior, but they are not as effective as instructions on an ILCS. This makes sense since, although the presence of first responders is a direct confirmation of the incident presence, it does not provide information to the drivers on which lane to choose. As stated in the previous paragraph, the combination of directed information along with the confirmation from the presence of units on scene is the most effective. In conclusion, the impact of the first responder is strong but not as strong as a ‘strong’ ILCS message, and the presence of a first responder does not effectively replace the ILCS system.

Although not securely defined, the presence of a crash-related DMS message upstream of the ILCS and the incident location has minimal but observable additional effect on lane change rates. Unfortunately, the incident events observed did not allow observation of the DMS without the ILCS being active, so it is not possible to compare them. The reason for the weak results obtained is because the DMS is upstream of the MTO camera views; therefore, none of the potential lane changing behavior between the DMS and the next ILCS was captured. In conclusion, from the current findings, the DMS contributes positively to the incident management effort albeit not largely enough to justify a DMS-ILCS pairing as a cost-effective strategy. Actually, as already mentioned, the presence of a first responder has a positive impact on lane changes, which is much more significant than the DMS.

Finally, from all the events observed, a qualitative observation of ILCS operation in view of heavy congestion can be made. Specifically, the ILCS are becoming ineffective under stop-and-go conditions. Beyond the simple logic of this statement, stemming from the fact that a lane selection system stops being effective when lane changes are impossible, there is a finer interesting detail of note. It was observed that in most cases the ILCS were capable of emptying the incident lane well upstream of the obstruction caused by the incident, even when the next lane was considerably congested. As noted in prior research on the merits of work zone zipper-merge in such situations, wasting storage by emptying a lane early may not be the most efficient strategy. Overall, utilizing the ILCS to induce lane changes out of the incident lane can not only become ineffective but also may be detrimental if the freeway section is under stop-and-go conditions. After a certain point, the preferred operational strategy may be to switch off the ILCS messages or display an innocuous message rather than instruct drivers to change lanes. The latter is even more relevant if a first responder protecting the incident scene is already present.

Given the plethora of options and combinations of incident management strategies possible with an ILCS system, even more if combined with first responders and other information sources, the limited resources available for this project did not allow an exhaustive evaluation and ranking. Regardless, good planning, prioritization, and close collaboration with RTMC engineers allowed for some strong and revealing results that answer pertinent questions. The work is not finished since other important questions remain. For example, this project evaluated the effectiveness of the ILCS system, but it did not compare it against other methods like DMS-only systems and certainly did not venture into which methodology is the most cost effective given price and maintenance needs. These questions are certainly easier to answer following this work, but are left for future research.