DEPARTMENT OF TRANSPORTATION

Evaluation of the Smart Work Zone Speed Notification System

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16. Abstract (Limit: 250 words)

The Smart Work Zone Speed Notification (SWZSN) system aims to alleviate congestion, queuing, and rear end crashes in work zones by informing drivers of the speed of the downstream segment using a type of portable Intelligent Lane Control System (ILCS), Portable Changeable Message Signs (PCMS). The hypothesis was that drivers, knowing the speed up to 1 mile downstream, will slow down early or at least be alert and perform smoother decelerations. Video of the SWZSN was analyzed over two years of operation by the Minnesota Traffic Observatory. Overall, the system resulted in beneficial reductions of selected decelerations by the drivers. In situations where the messages communicated to the drivers were consistent and accurate, reductions of more than 30% in the selected deceleration rates were observed. Unfortunately, there were several cases where counterproductive or misleading messages were communicated to the drivers, prompting relative increases to the selected deceleration rates. The most important observation, stemming from both positive and negative influences, was that the speed notification system was noticed by drivers and resulted in a statistically significant influence on driving behavior, unlike other driver alert systems.

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EVALUATION OF THE SMART WORK ZONE SPEED NOTIFICATION SYSTEM

FINAL REPORT

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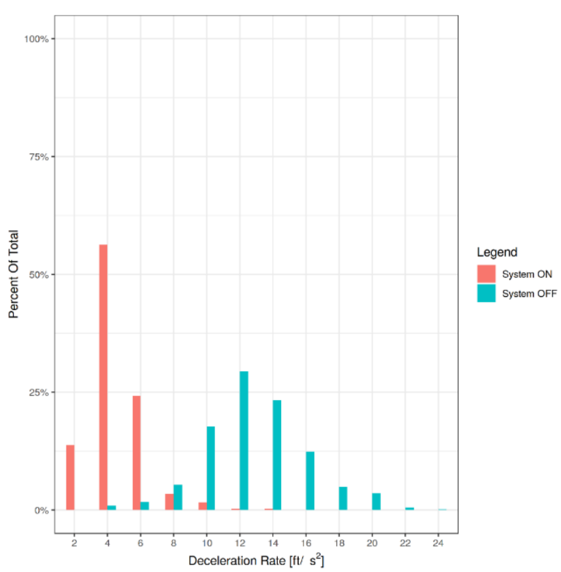
EXECUTIVE SUMMARY

The Smart Work Zone Speed Notification (SWZSN) system aims to alert drivers approaching a work zone to downstream congestion and queueing. SWZSN does this by informing drivers of the speed of the downstream segment, using a type of portable Intelligent Lane Control System (ILCS), Portable Changeable Message Signs (PCMS). The hypothesis is that drivers, knowing the speed up to 1 mile downstream, will preferably slow down early, or at least be alert to the queue and perform smoother decelerations avoiding rear-end collisions. The Minnesota Traffic Observatory (MTO) recorded video of the SWZSN in action to determine if the system was functioning. Cameras were moved in 2017 to optimize the performance of data extraction.

During the first year of the system's operation, based on empirical analysis of the messages generated, the project team identified discrepancies in the Speed Notification Algorithm, mostly in the form of unreasonable or delayed messages. The Regional Transportation Management Center (RTMC) never officially disclosed the logic used in the system, so during the project, it was difficult to know if any changes were implemented in the second year of the system's operation (2017). Regardless, during the 2017 construction season, the operation experienced a significant reduction in the earlier identified problematic operation. As clarified later, the algorithm logic did not change, but greater attention was spent on calibrating the Wavetronix speed sensors, hence producing better and less-noisy speed information to the real-time system.



Decelerations at the Johnson Pkwy Station. Reduced Lane Work Zone Layouts.

Overall, the Speed Notification system generally resulted in beneficial reductions of selected decelerations by drivers. In situations where the messages communicated to the drivers were consistent and accurate, reductions of more than 30% in the selected deceleration rates were observed.

Unfortunately, there were several cases where counterproductive or misleading messages were communicated to the drivers, prompting relative increases to the selected deceleration rates.

Using temporary detection on portable trailers rather than trying to utilize the permanent Wavetronix would have allowed for greater flexibility in detector placement to avoid obstructions caused by the work zone or to be placed in more strategic locations where queues developed. It would have also put the responsibility for detector calibration on the contractor rather than relying on MnDOT RTMC staff to recalibrate after a traffic switch. In addition, testing and refining a new system on a simpler construction project before trying to test it on one with complicated staging plans and traffic separated by multiple concrete barriers would have allowed RTMC staff with the assistance of the MTO to further refine the algorithm before deploying it.

Despite the issues with the system, the most important observation, stemming from both positive and negative influences, is that the system is noticed by the drivers and results in a statistically significant influence on driving behavior. This result is more than many other driver warning systems have achieved, and it suggests that downstream speed notification, as opposed to advisory speed limits, is an effective traffic control tool. The particular speed estimation and message generation algorithm could be improved to reduce the occurrences of misleading and counterproductive message combination.

CHAPTER 1: INTRODUCTION

Between Spring 2016 and Fall 2017, a 4.4-mile segment of I-94 east of downtown St. Paul was replaced in stages. To help mitigate the safety concerns associated with lane closures and the resulting congestion, MnDOT deployed a new system to alert drivers approaching and traversing the westbound portion of the work zone of downstream congestion and queuing. Systems with the same purpose have been tested in rural work zones, but mostly apply in locations where backups are predictable and develop from a specific location. Unlike the current variable speed limit system, which also detects congestion and provides advisory speeds to drivers, the new Smart Work Zone Speed Notification (SWZSN) system follows a different approach; it informs drivers of the speed of the downstream segment using Portable Changeable Message Signs (PCMSs).

It was envisioned that the new system would have greater success in reducing rear-end crashes on large, urban freeway work zones by promoting a more gradual speed reduction and reducing frequency of sharp decelerations caused by drivers being caught unaware by congestion or queues. This report describes the evaluation and refinement of the system while it was in use in the I-94 work zone in 2016 and 2017.

The primary objective of the project was to quantify the system's effects on drivers and determine its impact on the safety of the work zone. The data used for this task included video data collected downstream of the speed notification signs and at locations where queues frequently were encountered, detector data, and the PCMS message logs. Originally, radar sensors were going to be deployed to collect speeds throughout the work zone and quantify the speed reduction of the vehicles approaching the tail of the queue. Due to the prohibitive cost of instrumenting the entire work zone with radar, detector data from the MnDOT detector data feed – often from Wavetronix radar detectors – and computer-vision-based trajectory extraction were used as the sources of vehicle speed data.

MnDOT faced several challenges in deploying this new system on the I-94 corridor during the construction project. Prior to the I-94 construction project, staff at MnDOT's Regional Transportation Management Center (RTMC) had a project to replace all existing loop detector stations with Wavetronix microwave detection mounted on permanent poles spaced every half mile. Since the I-94 project would take out the existing loop detection and the plan was to deploy Wavetronix as the replacement for the loop detection, it was decided to deploy the Wavetronix ahead of the I-94 project to use those devices during construction. This proved to be quite challenging in that MnDOT could not relocate the detection to more strategic locations where queues were occurring since the detection was mounted on permanent poles rather than portable trailers. It also put more responsibility on MnDOT to recalibrate the Wavetronix detection after every traffic control change in the work zone rather than relying on the contractor to do this work.

Another challenge was the complicated staging that was in place during construction. Traffic lanes in the westbound direction at times were split between through trips, which were in a barrier separated lane for the length of the project and local trips, which were allowed to access local ramps. The project also used a moveable barrier to allow 3-lanes in the peak direction and 2-lanes in the off-peak direction. This complicated staging made calibration of the detection challenging as there were multiple concrete barriers in place, including the moveable barrier and the permanent barrier. In some locations, the Wavetronix sensors had to read across the active work zone as well as multiple barriers. Construction equipment or piles of material could sometimes interfere with the detection.

A lesson learned for MnDOT was to use temporary detection on portable trailers rather than try to use the permanent Wavetronix. This would have allowed for greater flexibility in detector placement to avoid obstructions caused by the work zone or for the portable trailers to be placed in more strategic locations where queues developed. It would have also put the responsibility for detector calibration on the contractor rather than rely on MnDOT RTMC staff to recalibrate after a traffic switch.

A second lesson learned was to test and refine a new system on a simpler construction project before trying to test it on one with complicated staging plans and traffic separated by multiple concrete barriers. This would have allowed RTMC staff with the assistance of the University of Minnesota to further refine the algorithm before deploying it.

Initially, the nine Minnesota traffic Observatory (MTO) cameras located at roughly half-mile increments along the work zone would constitute a large part of the video data collection system with MTO portable surveillance stations being used to selectively fill in the gaps in surveillance. Ultimately, due to the fact that the MnDOT cameras were frequently re-aimed by the RTMC, those camera feeds were left out of the video data collection plan. As described in fuller detail in Chapter 2: Deployment of Data Collection Equipment, the MTO camera stations were deployed at nine locations throughout the work zone — mounted on either MnDOT intelligent transportation system (ITS) poles or solar-powered trailers. The locations of equipment over the course of the two-year project can be seen in **Figure 1.2**. Data collection consisted of three parts: pre-SWZSN system deployment, post-SWZSN system deployment (phase I), and post-SWZSN system deployment (phase II), which correspond to the portion of the 2016 season before the first iteration of the system was brought online, the portion of the 2016 season after the system was brought online, and the entire 2017 work season, respectively.

The intended data analysis methods followed a two-part approach: comparison of queuing behavior when the system was operational versus when it was not; and a safety analysis comparing crash frequencies when the system was operational to crash frequencies when it was not. The portion of the analysis completed following the 2016 season was then used to help MnDOT engineers refine the SWZSN system algorithm.

While delays in equipment deployments in the early days of the project prevented the collection of detailed video data before the system was first deployed, the MTO was able to collect other forms of data while the system was offline. As described in Chapter 3, the manual data reduction methods used for the video data from the 2016 season provided insight into the general queuing patterns — such as queue location, extent, and duration — which was used to refine the data collection methods for the 2017 season. While the MTO was able to provide some feedback on the performance of the system, this task was made somewhat more difficult by the fact that the MTO was not provided with a description of the system code, much less the code itself, and was forced to reverse engineer the system.

As described in Chapter 4, the MTO developed a methodology for using a computer-vision-based Trajectory Extraction Tool (TET) before the 2017 data collection began to calculate vehicles' deceleration rates when encountering a queue using video alone. Based on the analysis of the 2016 data, cameras were repositioned in early 2017 to optimize the performance of the TET. Due to another unplanned break in the SWZSN system's operation in 2017, the MTO was able to collect video data with and without the system running. A timeline of these phases over the course of the two-year project can be seen in Figure 1.1. As described in Chapter 5: Final Data Analysis, the MTO used the calculated vehicle deceleration rates, detector speed data, and PCMS message logs to run a regression analysis to examine the effects of various combinations of sign messages and starting speeds on driver deceleration rates.

Figure 1.1 Data collection timeline from June 2016 through November 2016 (top), March 2017 through July 2017 (middle), and July 2017 through November 2017 (bottom).

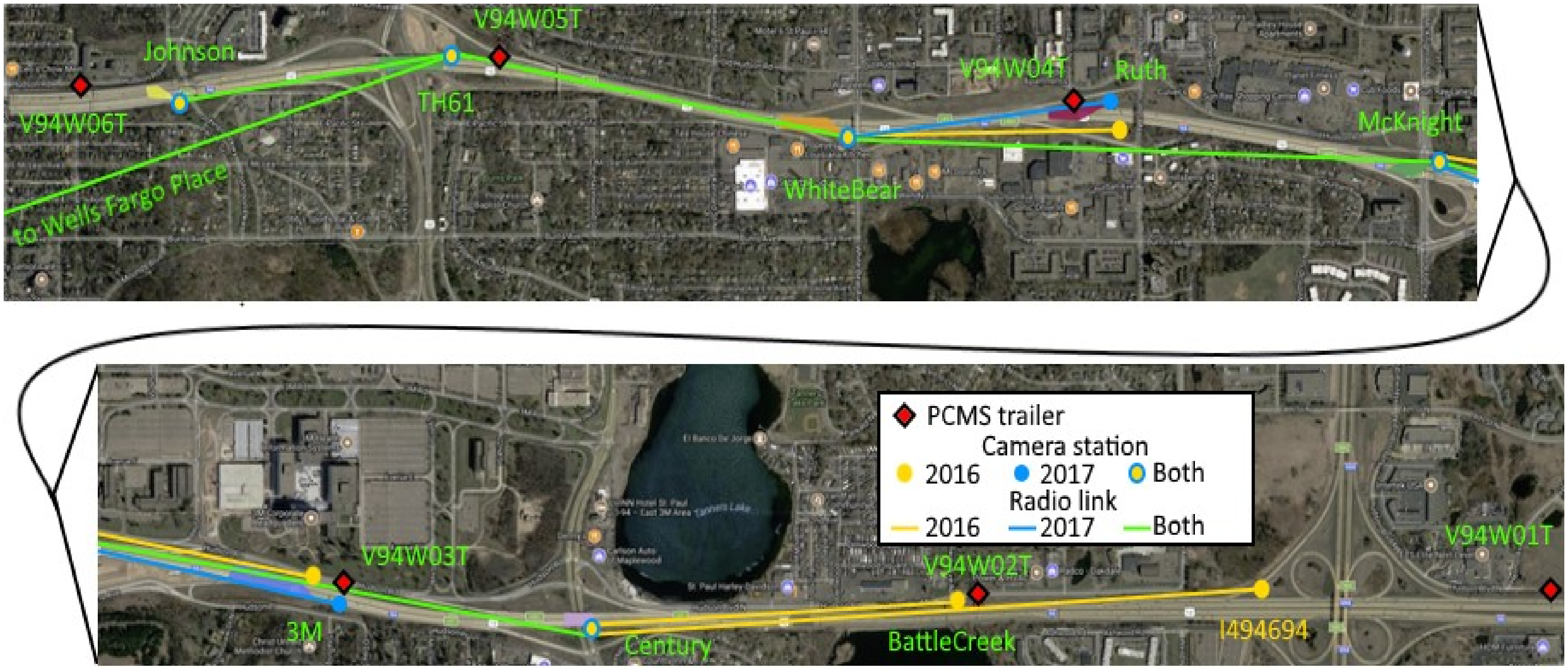


Figure 1.2 Work zone with PCMS trailers, camera stations, and radio links

CHAPTER 2: DEPLOYMENT OF DATA COLLECTION EQUIPMENT

Planning for the deployment of data collection equipment at the site began in early 2016 before the start of the construction season. The first step in this involved the selection of potential field sites for locating equipment and the preliminary field engineering to investigate visibility, and determine where equipment could be placed. The site selection process was undertaken in collaboration with RTMC engineers and construction project managers to optimize the data collection for the project schedule and given the available infrastructure. To allow for flexibility in the data collection, the MTO planned for the use of four solar-powered trailers that could be easily moved to adapt to the needs of construction and the observed traffic patterns. In addition to this, RTMC engineers allowed the MTO to use their existing ITS poles to place and provide power to equipment.

2.1 STATIONS

Ultimately, nine stations, consisting of five ITS pole-mounted stations and four trailer stations, were selected for deployment in 2016. In addition to the data collection equipment, provisions were also made to establish a communication network with the site to monitor and administer equipment from the MTO laboratory. Once this was decided, the additional equipment needed was procured for use on the project and stations were assembled for deployment. Following the first year of data collection, after which a preliminary analysis of the data collected was conducted, the equipment in the field was adjusted to convert two of the trailer stations to pole-mounted stations, and to remove the two furthest upstream stations, which were observed to rarely experience significant queueing.

2.1.1 2016 Deployment

The first step of the station selection process consisted of hypothesizing which regions of the work zone would see the most queuing. The backs of queues, where drivers encounter slower traffic and are forced to brake, were of the most interest. The MTO used basic traffic flow theory, queuing locations prior to construction, and the work zone traffic control plans to predict which parts of the work zone would be most likely to have the backs of queues. The research team hypothesized that queues would continue to originate downstream of Earl St at the beginning of rush of the AM and PM peaks, and propagate upstream. Because construction would decrease the number of lanes, the MTO further surmised that the queuing would be more intense and would likely extend further upstream of Johnson Ave early in the peak periods. Therefore, a camera station downstream of Johnson Ave would likely record very few vehicles encountering the back of a queue, as it would primarily be recording vehicles already in the queue; Earl St was set as the downstream limit of video collection. The research team was unsure how far upstream congestion would reach, but predicted that it was unlikely to extend beyond the I-94/494/694 interchange; the interchange became the upstream limit of video collection. The MTO then consulted with the RTMC to compile a list of eight MnDOT ITS and NID poles in this region. Between Earl St and Century Ave, the poles were separated by roughly half of a mile.

The MTO selected nine locations at roughly half mile intervals between Johnson Pkwy and the I-94/494/694 interchange to deploy cameras. Five of the stations were mounted on MnDOT's crank tip-down poles at Johnson Pkwy (known as "Johnson station"), TH-61 (known as "TH61 station"), White Bear Ave (known as "White Bear station"), McKnight Rd (known as "McKnight station"), and Century Ave (known as "Century station"). The poles provided a high, steady vantage point for recording vehicles and, following MnDOT giving the MTO access to the poles' control cabinets, a power source.

At locations that did not have a suitable pole, the MTO deployed stations mounted on solar-powered trailers. Two of the trailers were bought used and the other two were rented for the duration of the project. These stations were located at Ruth St (known as "Ruth station"), at 8th St in front of the 3M headquarters (known as "3M station"), at Greenway Ave by Battle Creek Lake (known as "Battle Creek station"), and at the on-ramp from southbound 494/694 (known as "I494694 station"). Ruth station was placed on a trailer on the south side of I-94 instead of on the pole on the north side as the pole did not have a crank to tip it down, making equipment installations and adjustments very difficult. The south side had a flat, elevated area to park a trailer. 3M station was placed on a trailer on the north side of I-94, partly because the NID pole on the south side did not have a crank, as well as to provide a clearer view of westbound traffic. The two upstream stations were located on trailers because of the lack of MnDOT poles with power and because the extent of queuing in that area was the most uncertain. The trailers provided mobility in the event that the stations needed to be moved to get a better view.

The camera stations were deployed over the course of June 2016 which took an MTO engineer 160 hours with assistance from another engineer or undergraduate research assistant. Over the course of the 2016 season, the trailer stations had to be moved a handful of times in order to keep them from interfering with construction or traffic operations. To stay up to date on the construction work and traffic control plan, an MTO engineer attended weekly meetings with the construction project managers for the majority of the 2016 season.

Initially, the eight MnDOT cameras along the work zone (see Figure 2.1) were going to be used as part of the video data collection system but, early on, this proved to be infeasible. The MnDOT cameras are all mounted on remote-controlled pan-tilt-zoom (PTZ) mounts controlled by MnDOT via the RTMC. Any time MnDOT or State Patrol personnel wish to investigate an incident along the corridor, they are able to control the direction and zoom of the camera. While this is useful for traffic management and emergency response, the frequent changes in camera views was a prohibitive factor for use by the MTO.

To get a qualitative sense of the queuing behavior of the entire video data collection region, the MTO decided to aim all of its cameras downstream to maximize the observable area of the work zone and provide a view of westbound vehicles' brake lights – a tell-tale sign of queuing. When possible, the cameras were to be located and aimed so that they could record vehicles passing the PCMS trailers.

To improve the camera angles for the extraction of trajectories from video (see Chapter 4), most of the cameras were repositioned in late September 2016 to test the relative quality of the trajectory extraction. The stations were then deactivated for the winter and the trailer stations were retrieved from the field. During the period between the two seasons, testing of the trajectory extraction was

Figure 2.1 MnDOT cameras C855 – C862 along the work zone

performed to determine if the new camera angles would be sufficient for collecting the data needed. While the new positions showed improved quality of the data extracted over the previous angles, it was still not sufficient and so further adjustments, discussed in the next section, were made at the beginning of the 2017 season.

During the 2016 construction season, video data was collected at each of the nine deployed cameras from 6 a.m. to 8 p.m. every day of the week between July 2nd and September 29th. Video data was collected before and after the system was brought online on August 5th. In total, video was collected on 142 days, 51 of which had a full day of video from every camera.

2.1.2 2017 Deployment Adjustments

Using the information collected on the queuing patterns in 2016 (see 3), some changes were made in April of 2017. The two trailer stations that were furthest upstream (BattleCreek and I494694) were not redeployed for the 2017 season because queues rarely reached those points in the work zone. The remaining two trailer stations (Ruth and 3M) were transferred to NID poles which, though more difficult to work with than the ITS poles and trailers, allowed for better positioning of the cameras. The use of poles also allowed for constant power from infrastructure, and eliminated the need to move stations that might obstruct construction, as was necessary with trailers.

In addition to these changes, the cameras at each station were also raised to the top of the pole to improve the camera angle for better trajectory extraction. This made it difficult to aim the cameras, however, since a ladder could no longer reach the cameras after the pole was raised. To address this, the camera mounts were fitted with off-the-shelf pan-tilt mounts that allowed adjusting the aim of the camera remotely through the web interface, eliminating the need to raise and lower the poles repeatedly to adjust the camera angle. All seven of the cameras were aimed to optimize them for computer-vision-based extraction of the trajectories of vehicles on the 2017 road layouts. The camera angles were chosen at each location to maximize the portion of the image where vehicles were not occluded by nearby infrastructure (e.g. light poles and signs) while focusing on the area closest to the camera. The height of the cameras also allowed adjacent vehicles to be more easily distinguished from one another, improving the resulting trajectory data. While the initial camera deployment in 2016 took a 2-person team approximately four weeks, this repositioning was achieved in approximately one week. Camera locations and views from 2016 and 2017 can be seen in Figure 2.2 through Figure 2.33.

During the 2017 construction season, video data was collected at each of the seven deployed cameras from 6 a.m. to 8 p.m. every day of the week between April 8th and November 21st. Video data was collected before and after the system was brought online on July 11th. In total, video was collected on 233 days, 142 of which had a full day of video from every camera.

2.1.3 Equipment Locations and Camera Views

This section shows the location, field of view, and view directly from the camera at each of the nine deployment sites

Figure 2.2 Aerial view of the field of view of the camera at Johnson station in 2016

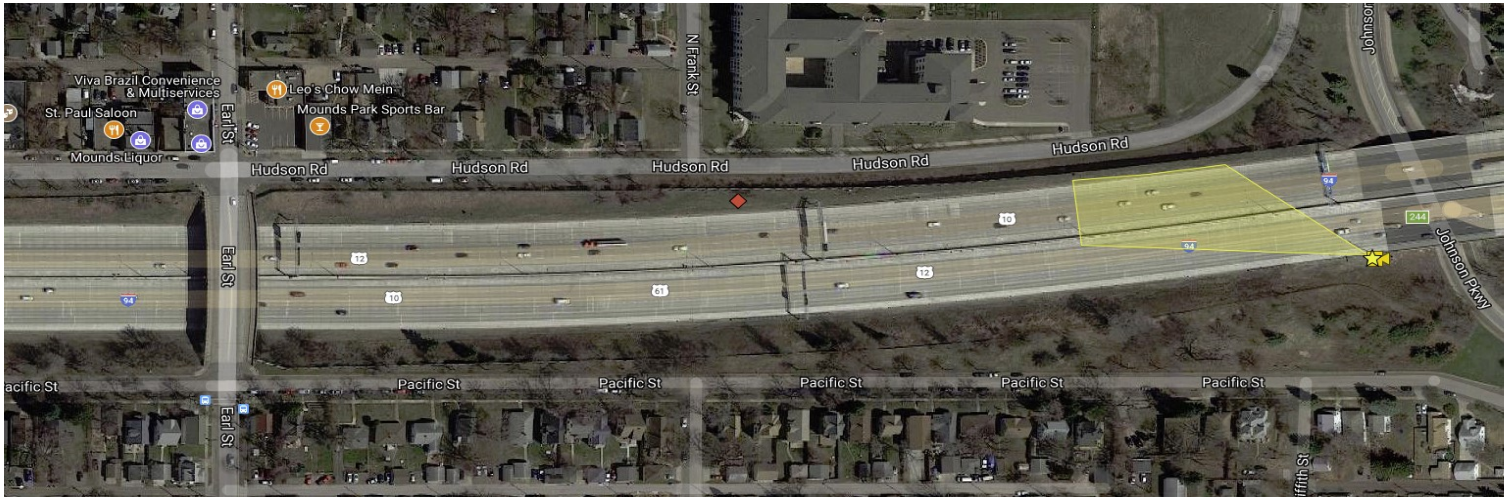


Figure 2.3 Aerial view of the field of view of the camera at Johnson station in 2017

Figure 2.4 Camera view for the camera at Johnson station in 2016

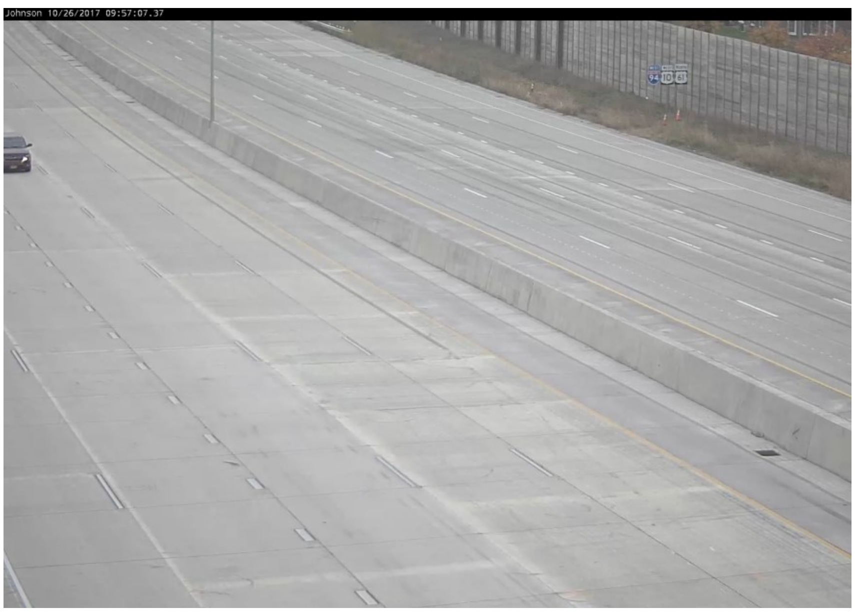


Figure 2.5 Camera view for the camera at Johnson station in 2017

The camera at Johnson station was mounted on MnDOT camera pole C856. In 2016, it was aimed downstream to capture as much of the queue formation process as possible (see Figure 2.2 and Figure 2.4). In 2017, the camera was turned down and to the left to give a closer top-down view of vehicles passing the station to help improve the accuracy of the data produced with the TET (see Figure 2.3 and Figure 2.5).

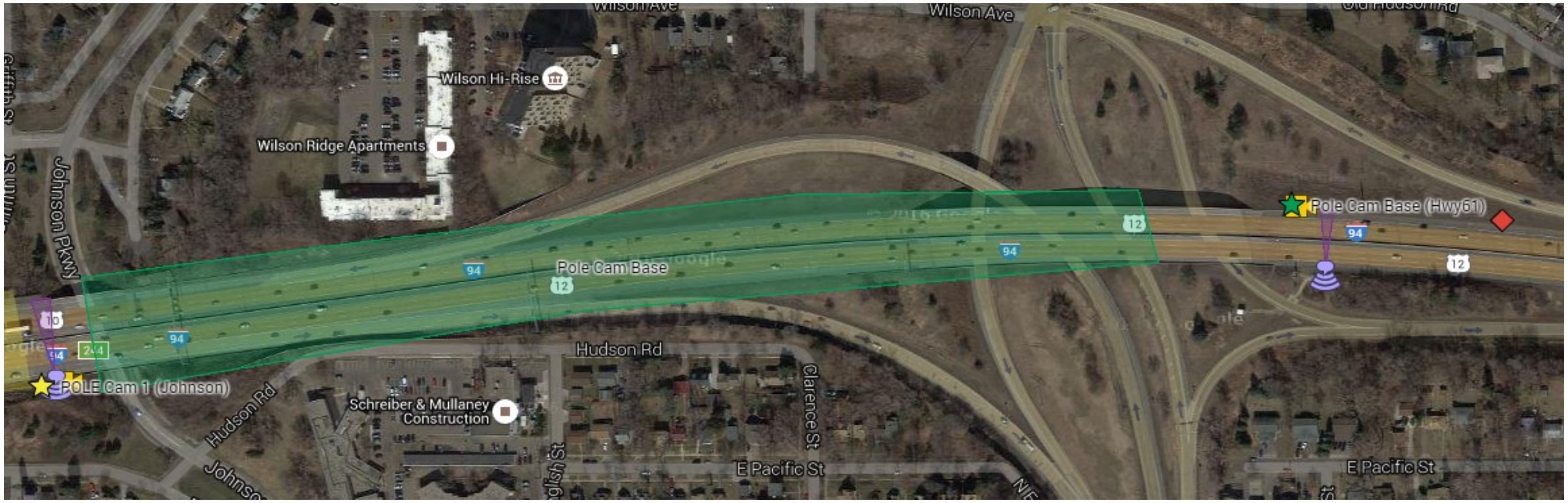


Figure 2.6 Aerial view of the field of view of the camera at TH61 station in 2016

Figure 2.7 Aerial view of the field of view of the camera at TH61 station in 2017

Figure 2.8 Camera view for the camera at TH61 station in 2016

Figure 2.9 Camera view for the camera at TH61 station in 2017

The camera at TH61 station was mounted on MnDOT camera pole C857. In 2016, it was aimed downstream to capture as much of the queue formation process as possible (see Figure 2.6 and Figure 2.8). In 2017, the camera was turned down and mounted higher on the pole to give a closer top-down view of vehicles passing the station to help improve the accuracy of the data produced with the TET (see Figure 2.7 and Figure 2.9).

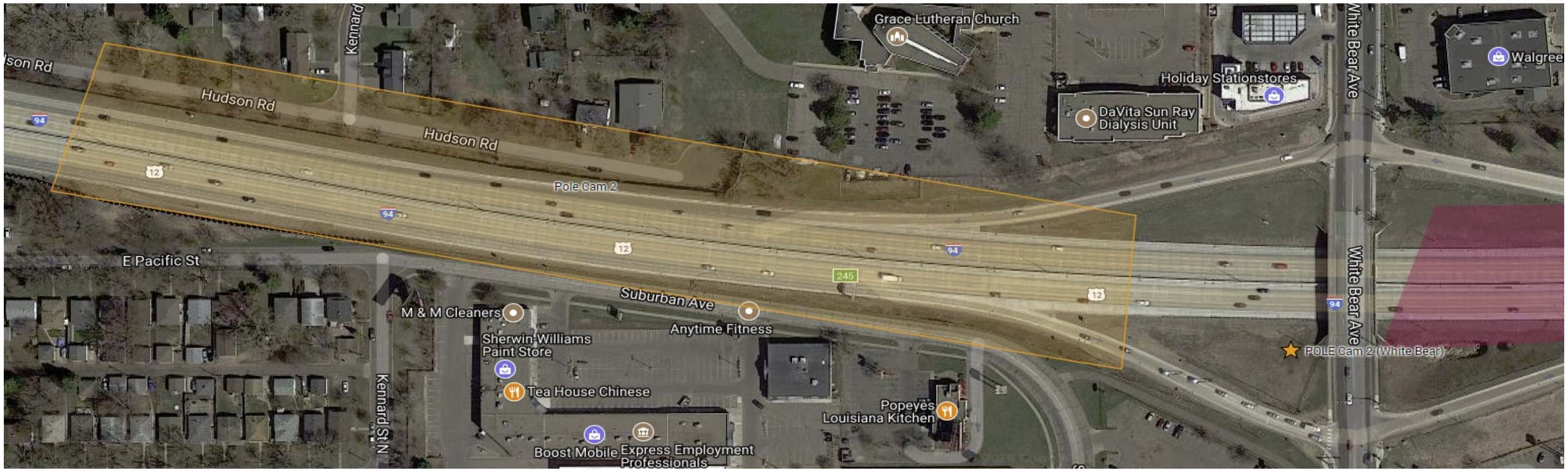


Figure 2.10 Aerial view of the field of view of the camera at White Bear station in 2016

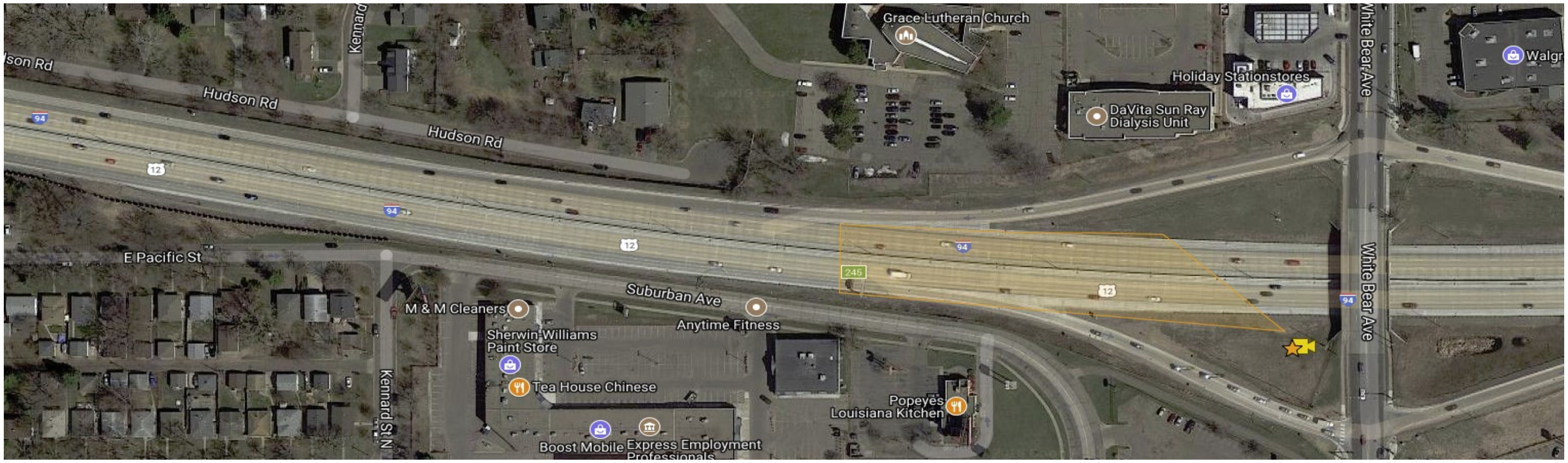


Figure 2.11 Aerial view of the field of view of the camera at White Bear station in 2017

Figure 2.12 Camera view for the camera at White Bear station in 2016

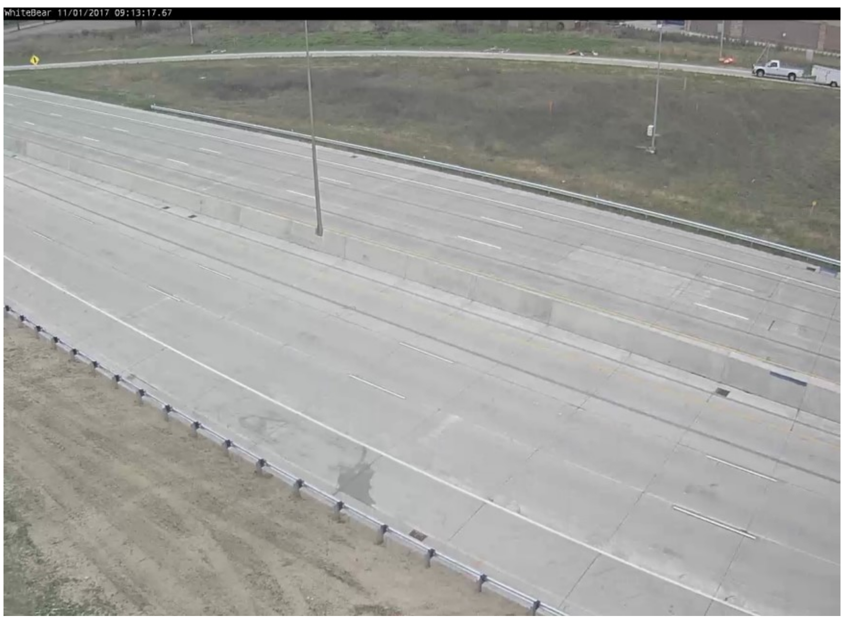


Figure 2.13 Camera view for the camera at White Bear station in 2017

The camera at WhiteBear station was mounted on MnDOT camera pole C858. In 2016, it was aimed downstream to capture as much of the queue formation process as possible (see Figure 2.10 and Figure 2.12). In 2017, the camera was turned down and to the right to give a closer top-down view of vehicles passing the station to help improve the accuracy of the data produced with the TET (see Figure 2.11 and Figure 2.13).

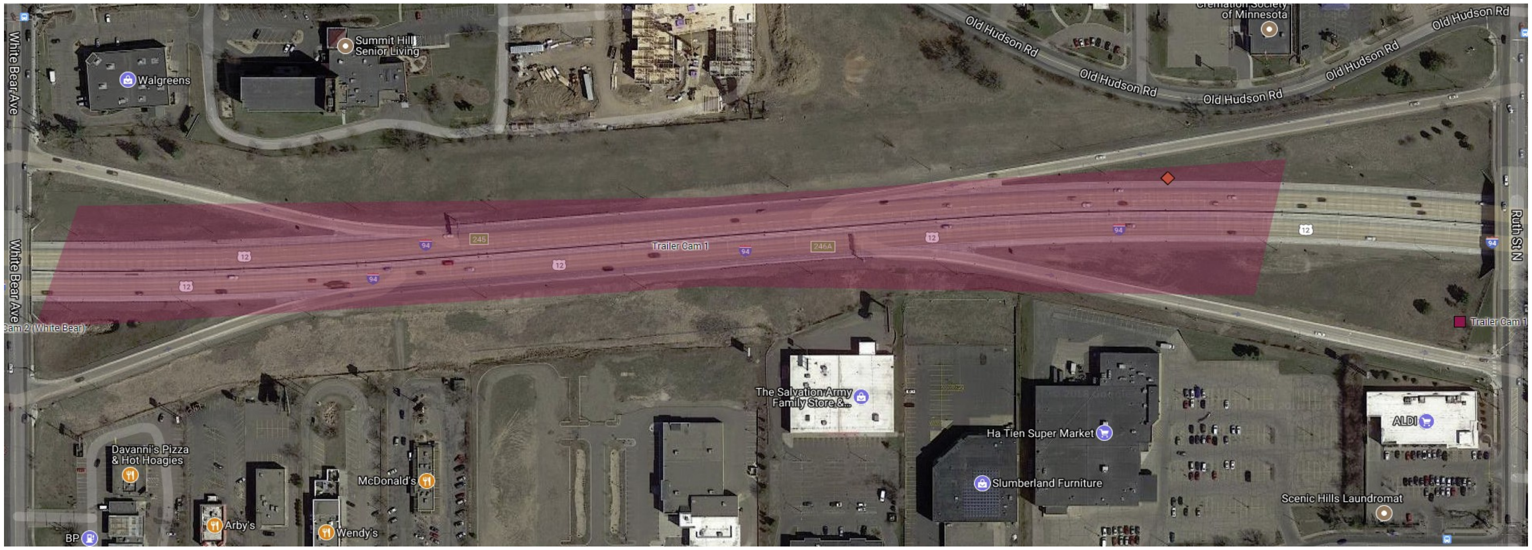


Figure 2.14 Aerial view of the field of view of the camera at Ruth station in 2016

Figure 2.15 Aerial view of the field of view of the camera at Ruth station in 2017

Figure 2.16 Camera view for the camera at Ruth station in 2016

Figure 2.17 Camera view for the camera at Ruth station in 2017

The camera at Ruth station was mounted on a solar-powered trailer to the south of I-94 and to the west of Ruth St N in 2016 where it was aimed downstream to capture as much of the queue formation process as possible (see Figure 2.14 and Figure 2.16). In 2017, the camera was moved to the MnDOT NID pole on the north side of I-94 west of Ruth St, where it was aimed to give a closer top-down view of vehicles passing the station thereby helping to improve the accuracy of the data produced with the TET (see Figure 2.15 and Figure 2.17).

Figure 2.18 Aerial view of the field of view of the camera at McKnight station in 2016

Figure 2.19 Aerial view of the field of view of the camera at McKnight station in 2017

Figure 2.20 Camera view for the camera at McKnight station in 2016

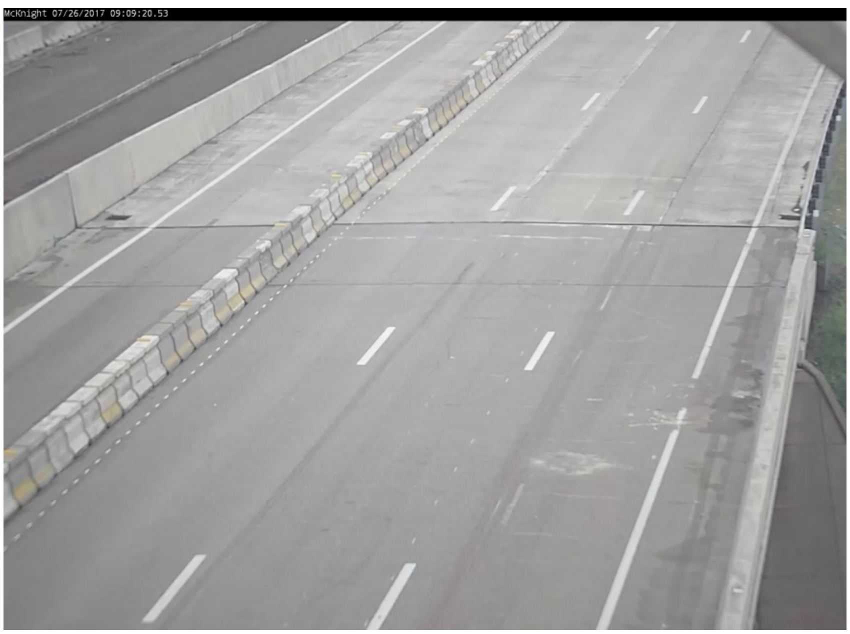


Figure 2.21 Camera view for the camera at McKnight station in 2017

The camera at McKnight station was mounted on MnDOT camera pole C859. In 2016, it was aimed downstream to capture as much of the queue formation process as possible (see Figure 2.18 and Figure 2.20). In 2017, the camera was turned down and to the left to give a closer top-down view of vehicles passing the station to help improve the accuracy of the data produced with the TET (see Figure 2.19 and Figure 2.21).

Figure 2.22 Aerial view of the field of view of the camera at 3M station in 2016

Figure 2.23 Aerial view of the field of view of the camera at 3M station in 2017

Figure 2.24 Camera view for the camera at 3M station in 2016

Figure 2.25 Camera view for the camera at 3M station in 2017

The camera at 3M station was mounted on a solar-powered trailer to the north of I-94 in front of the 3M corporate headquarters in 2016 where it was aimed downstream to capture as much of the queue formation process as possible (see Figure 2.22 and Figure 2.24). In 2017, the camera was moved to MnDOT NID pole on the south side of I-94 west of Sterling St, where it was aimed to give a closer top-down view of vehicles passing the station thereby helping to improve the accuracy of the data produced with the TET (see Figure 2.23 and Figure 2.25).

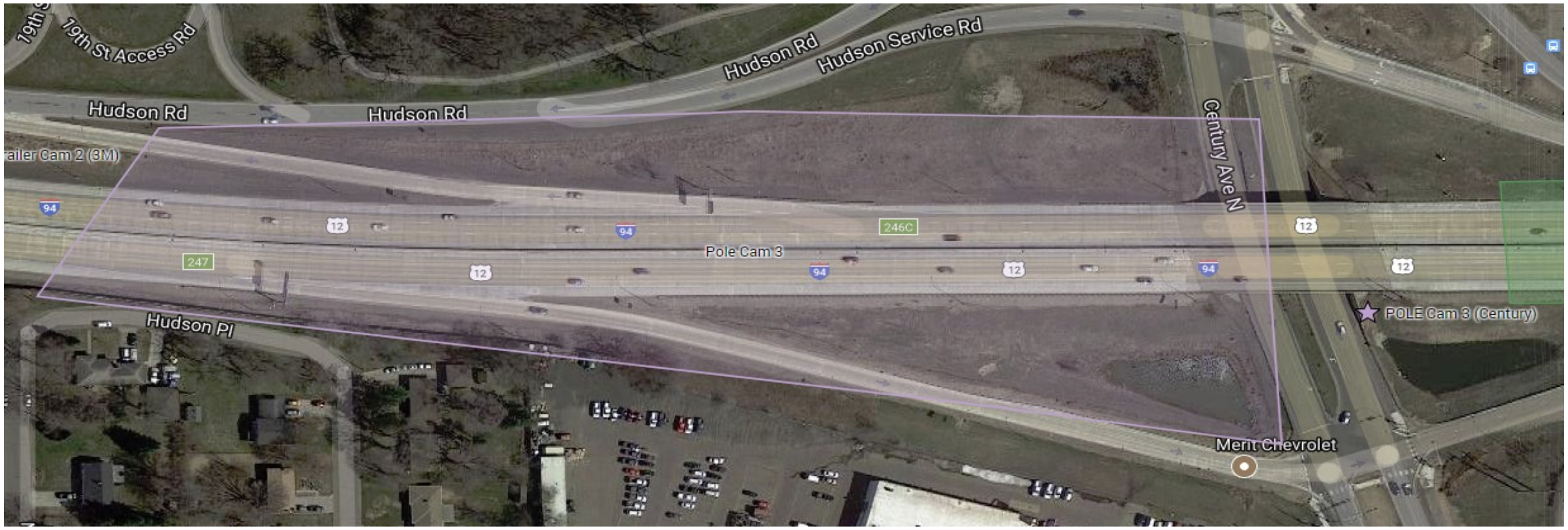


Figure 2.26 Aerial view of the field of view of the camera at Century station in 2016

Figure 2.27 Aerial view of the field of view of the camera at Century station in 2017

Figure 2.28 Camera view for the camera at Century station in 2016

Figure 2.29 Camera view for the camera at Century station in 2017

The camera at Century station was mounted on MnDOT camera pole C860. In 2016, it was aimed downstream to capture as much of the queue formation process as possible (see Figure 2.26 and Figure 2.28). In 2017, the camera was turned down and to the right to give a closer top-down view of vehicles passing the station to help improve the accuracy of the data produced with the TET (see Figure 2.27 and Figure 2.29).

Figure 2.30 Aerial view of the field of view of the camera at Battle Creek station in 2016

Figure 2.31 Camera view for the camera at Battle Creek station in 2016

The camera at Battle Creek station was mounted on a solar-powered trailer to the north of I-94 and near Greenway Ave N in 2016 where it was aimed downstream to capture as much of the queue formation process as possible (see Figure 2.30 and Figure 2.31). The camera was removed at the end of the 2016 season because very few queues extended far enough upstream to be visible from this station.

Figure 2.32 Aerial view of the field of view of the camera at the I-494/694 station in 2016

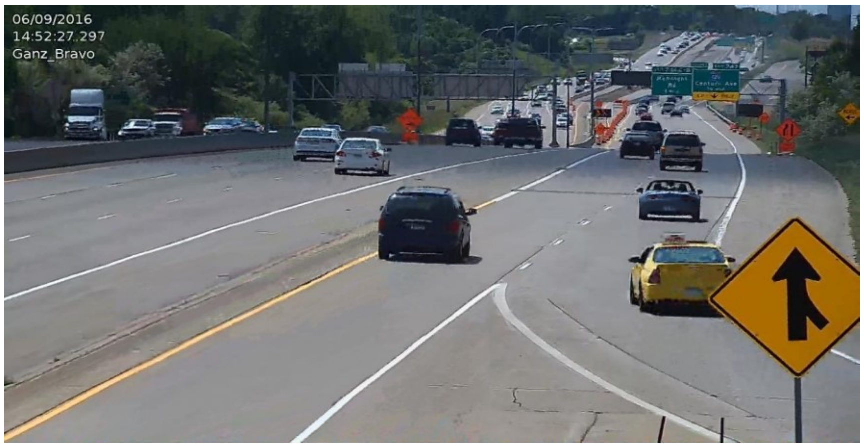


Figure 2.33 Camera view for the camera at I494/694 station in 2016

The camera at the I-494/694 station was mounted on a solar-powered trailer on the north side of I-94 and slightly upstream of the on-ramp from I-494/964 SB. During the 2016 data collection period it was aimed downstream to capture as much of the queue formation process as possible (see Figure 2.32 and Figure 2.33). The camera was removed at the end of the 2016 season because rarely queues extended far enough upstream to be visible from this station.

2.2 COMMUNICATION

To improve the reliability of the data collection, the deployment plan involved the development of a communication link to connect the equipment in the field to the MTO's network. Because of the distance between the field sites and the MTO Laboratory in the Civil Engineering Building – ranging from 9 to 13 miles away – the most cost-effective solution for connecting to these sites was to establish a wireless radio link between the University and the equipment in the field, much like the MTO's I-94 Field Laboratory in downtown Minneapolis. Advancements in radio technology have allowed such devices to deliver good performance for an affordable price, providing flexibility for creating networks that span a large area like this one.

The MTO already had a fiber optic link to the rooftop of Malcom Moos Tower on the University of Minnesota's Minneapolis campus which served as an ideal vantage point for communication with distant sites. Because the radios require a clear line of site to be effective, the other end of this leg of the radio link needed to have a clear line of site to both Moos Tower and the work zone. Due to geographic features in the area between the University and the site, a direct radio link was not feasible, so a relay station taking advantage of the tall buildings in downtown St. Paul was added to complete the connection. The rooftops of two buildings in St. Paul's central business district were selected as options. The first, Wells Fargo Place, is a 471-foot office building and the second, The Pointe of Saint Paul, is a 340-foot apartment high-rise.

After visiting both rooftops to confirm that they provided adequate line of site to both the work zone and Moos Tower and could handle the equipment installation, the MTO requested quotes for the cost of the space needed to install a radio relay station. The management of Wells Fargo Place responded with a much lower bid, in part because of the U of M's status as a research institution, and was selected as the location for the relay station. The MTO obtained a lease on the roof of Wells Fargo Place to cover the duration of the project and installed the equipment needed to create the link between Moos Tower and Wells Fargo Place. The MTO also established a similar link between Wells Fargo Place and a station mounted on MnDOT camera pole C857, the camera pole with the clearest line of site to Wells Fargo Place, to finish the connection to the field installation. Because of the size of the pole and the mounting hardware that came with the radio, this required custom adapter parts to be manufactured by the University's machine shop. In all, the arrangement and deployment of this communication link took approximately 80 hours of combined effort over the course of several weeks.

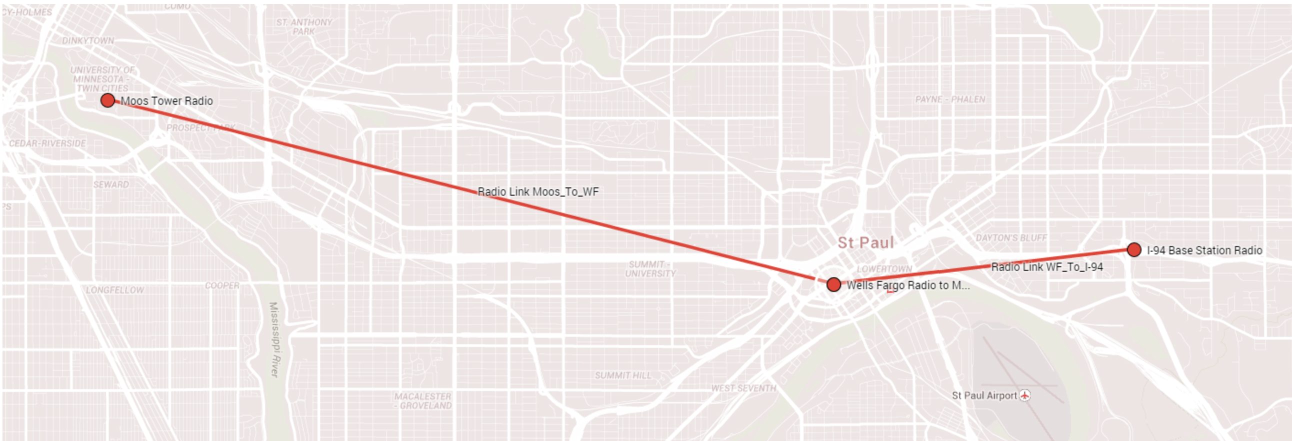


Figure 2.34 MTO radio link to I-94 work zone

The original plan for extending the communication network to other stations in the work zone was to use a single sector antenna mounted on MnDOT camera pole C857 to communicate with smaller station radios on each of the roadside stations along the work zone. Unfortunately, the distance, topography, and sources of interference along the corridor prevented the MTO from extending the signal east of White Bear Ave. To work around this, researchers established a number of additional relay stations to link all of the stations back to the base station on pole C857 (referred to in subsequent text as “station TH61”). Figure 2.34 shows this radio relay.

This provided connectivity to all stations in the field, allowing the devices to be reached from the MTO’s network in the lab. Originally this link was planned to support not only monitoring of the data collection and administering the system, but also downloading the video collected from the field for viewing and storage in the lab. Though the initial tests conducted before deploying the relay stations made it appear that this would be possible, after deploying the equipment additional interference in the area reduced the stability of the connection enough to make downloading the video from all stations infeasible. Much of this was attributed to the operation of a wireless Internet Service Provider (ISP) that activated equipment in the vicinity of Wells Fargo Place after the University’s deployment. This ISP used similar hardware that operated on unlicensed frequency bands like the radios used by the University, causing excessive noise that significantly reduced bandwidth. Despite this, the connection was stable enough to allow consistent monitoring of the data collection, however, the high latency of the connection made this difficult at times. To work around this, researchers developed a set of monitoring tools that used a low-bandwidth Secure Shell (SSH) connection to send status information and sample images back to the lab periodically. These tools, which capitalized on tools that had already been developed, took an additional 20 hours of effort to develop and integrate with the system in place.

While the monitoring system allowed researchers to ensure that any interruptions to the data collection were kept to a minimum, the large amount of video data recorded still required physical site visits to retrieve the video. Initially this was done by individually visiting each site to collect the flash drives used to store the video. This proved to be very time consuming due to the difficulty of accessing the stations, so researchers installed high-capacity hard drives at the TH-61 base station that were used to store video from all stations and allow retrieval by visiting a single site. This took advantage of the relatively high bandwidth connections between the field stations which, unlike the link back to the University, were robust enough to support the needed data transfer rates.

During the 2017 season, increasing unreliability of the radio link led researchers to install a 4G cellular modem at the TH-61 base station as an alternate means of communication with the site. This provided a lower-latency and higher-bandwidth connection to the stations in the field, allowing the camera streams to be viewed in real-time for short periods of time, albeit at a greater financial cost. This proved useful at several points, however, as it allowed adjusting camera positioning using remotely-controllable pan-tilt mounts that were installed in 2017 to accelerate the camera aiming process.

CHAPTER 3: PRE-SYSTEM DEPLOYMENT AND POST-SYSTEM DEPLOYMENT (PHASE I) DATA REDUCTION AND ANALYSIS

After the collection of data in 2016, a preliminary analysis of the field conditions was carried out to assess the performance of the system and suggest improvements. The collected information was also analyzed to evaluate the placement of video collection equipment to capture both the congestion in the corridor and the feasibility of using the video for computer-vision-based trajectory extraction. The following chapter describes the data reduction and visualization methods that were employed, along with a brief description of the experimentation conducted with the trajectory extraction tool.

3.1 VIDEO DATA REDUCTION

The objective of the data collection during 2016 was to identify the extent and growth rate of queues in the work zone. This data was collected by undergraduate students employed by the MTO who watched several days' worth of video and recorded the location and the timespan that the queue was at a given location for each of the nine cameras. Although video was available for most cameras since June 20th, 2016, for the purposes of a unified analysis the period between July 5th to July 15th is included in the results presented in this section.

Each camera view was divided into three or four regions; undergrads noted the time of day that the back of a queue first extended into to a region and the time that the back of the queue receded back upstream of that region. Figure 3.1 shows the four regions in the video from 3M station.

Figure 3.1 Camera 6 Queue End location regions

3.2 DATA VISUALIZATION

To show the progression of queues in both space and time, the queue location data for each day was compiled and plotted by order of physical location. Figure 3.2 shows an example of a queue location plot with the regions from the camera views on the y-axis (progressing upstream from Johnson-A to 494/694-B) and the time of day (from 6:00 to 10:00 a.m.) on the x-axis. The black areas denote times where the corresponding region on the y-axis was occupied by a queue.

A more informative view of the queuing behavior was produced by combining the queue location plots for the days analyzed into one queue location summary plot. In Figure 3.3, the percentage of the days sampled where a queue was present at a given location and time is shown. Darker areas indicate locations and times of frequent queueing while lighter grey areas show areas where queues were observed less frequently or less consistent.

3.2.1 Detector Data

All available data for all detectors in the westbound lanes of I-94 between County Road 13 and Kellogg Blvd was imported from the MnDOT detector data feed. When available, in cases where radar sensors were used, speed data was imported directly but, in most cases, speed was estimated using the occupancy and volume data from loop detectors. In addition to the fact that some of the detectors were not in operation at various phases of the project, other issues with the data were encountered. Among the issues encountered were the resolution of the detector data (one data point every 30 seconds) and the limitations of estimating the speed from the volume and occupancy (an average vehicle length was assumed but vehicles significantly shorter or longer than the average resulted in noisy and potentially unrealistic speed data).

3.2.2 Heatmaps of Speed over Space and Time

To visually show the speeds from the detector data each day, the available speed data is plotted in a contour plot or heatmap. To do this, the available detector data is aggregated by station and then averaged. The resulting averages speed for each 30-second time step is represented by a color ranging from red to green with red corresponding to a speed of 0 mph and green corresponding to 80 mph. For each day of the evaluation period, the data for each station is plotted in ascending chronological order from left to right. The stations' data is then "stacked" on top of each other in the order that they would be encountered by drivers with the furthest upstream detector at the bottom of the plot and the furthest downstream detector at the top of the plot. The resulting plot shows the speeds at every station in 30-second increments for the whole day. An example of a heatmap for July 26th, 2017 is shown in Figure 3.4. The white bars are the result of no detector data being available at some stations due to the detectors being removed during construction. Unlike the SWZSNS which reports the speed of the lane with the lowest speed, the heatmaps show the average of all available lanes.

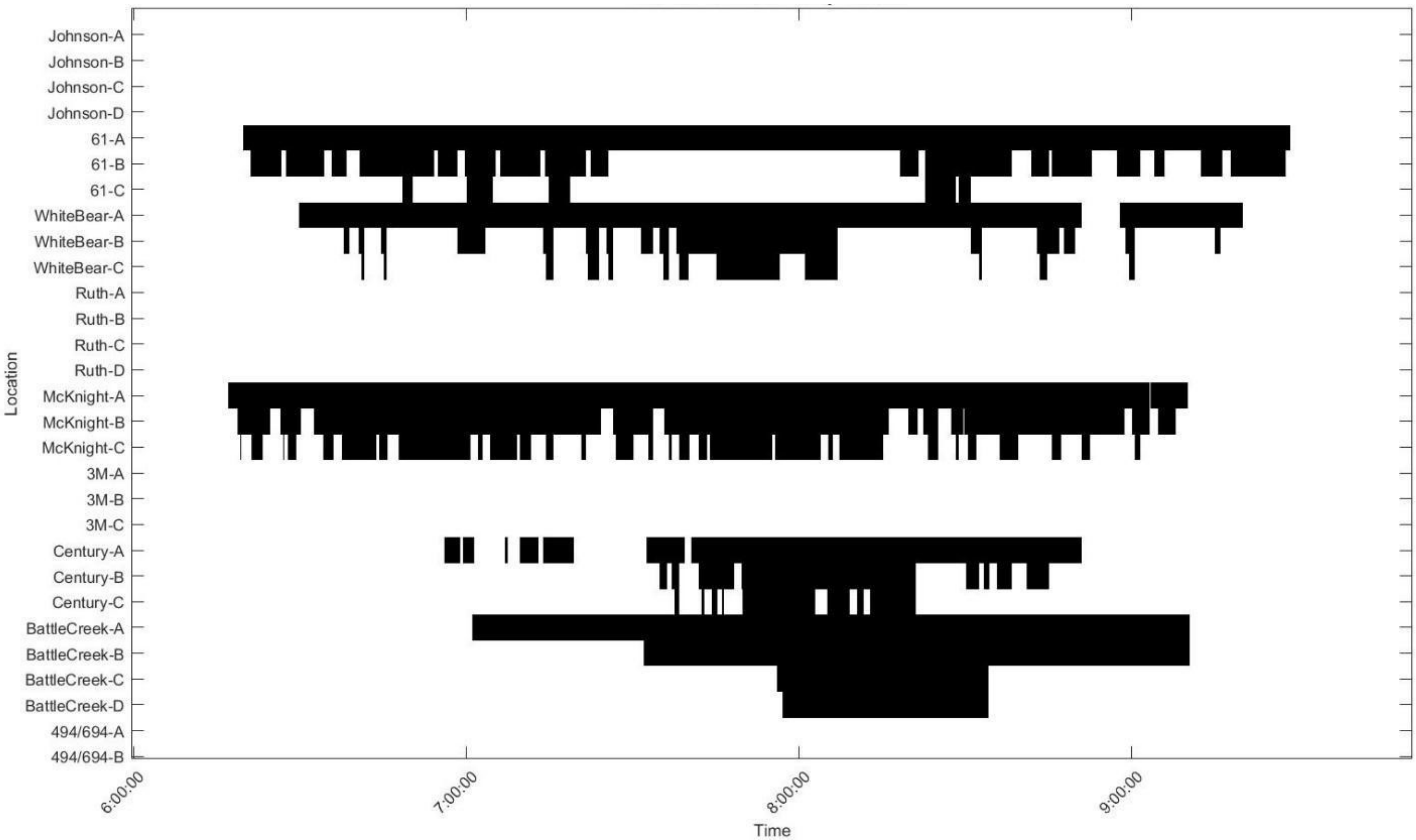


Figure 3.2 Queue location on I-94 WB by region and time of day

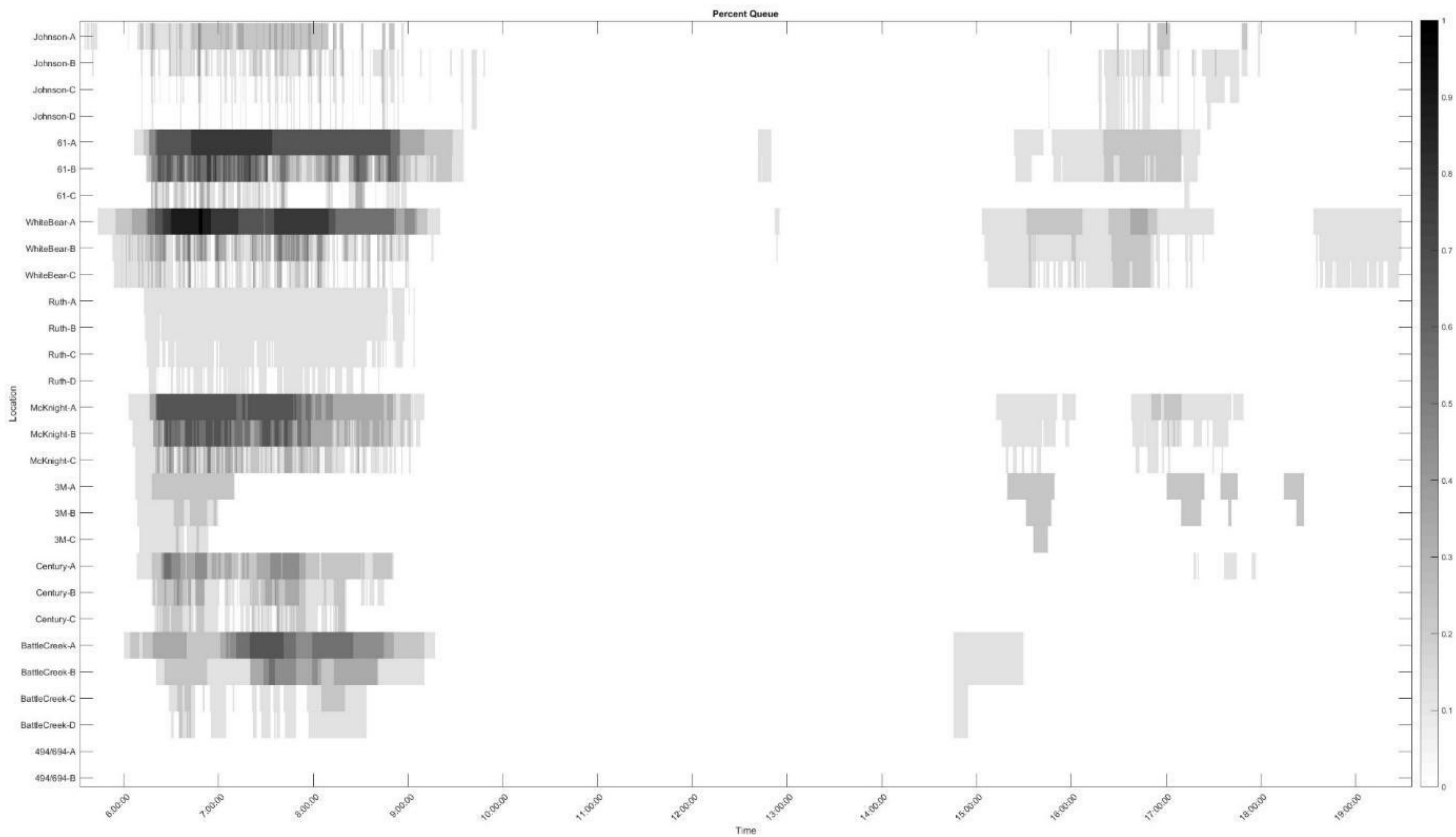


Figure 3.3 Queue frequency on I-94 WB by location and time of day

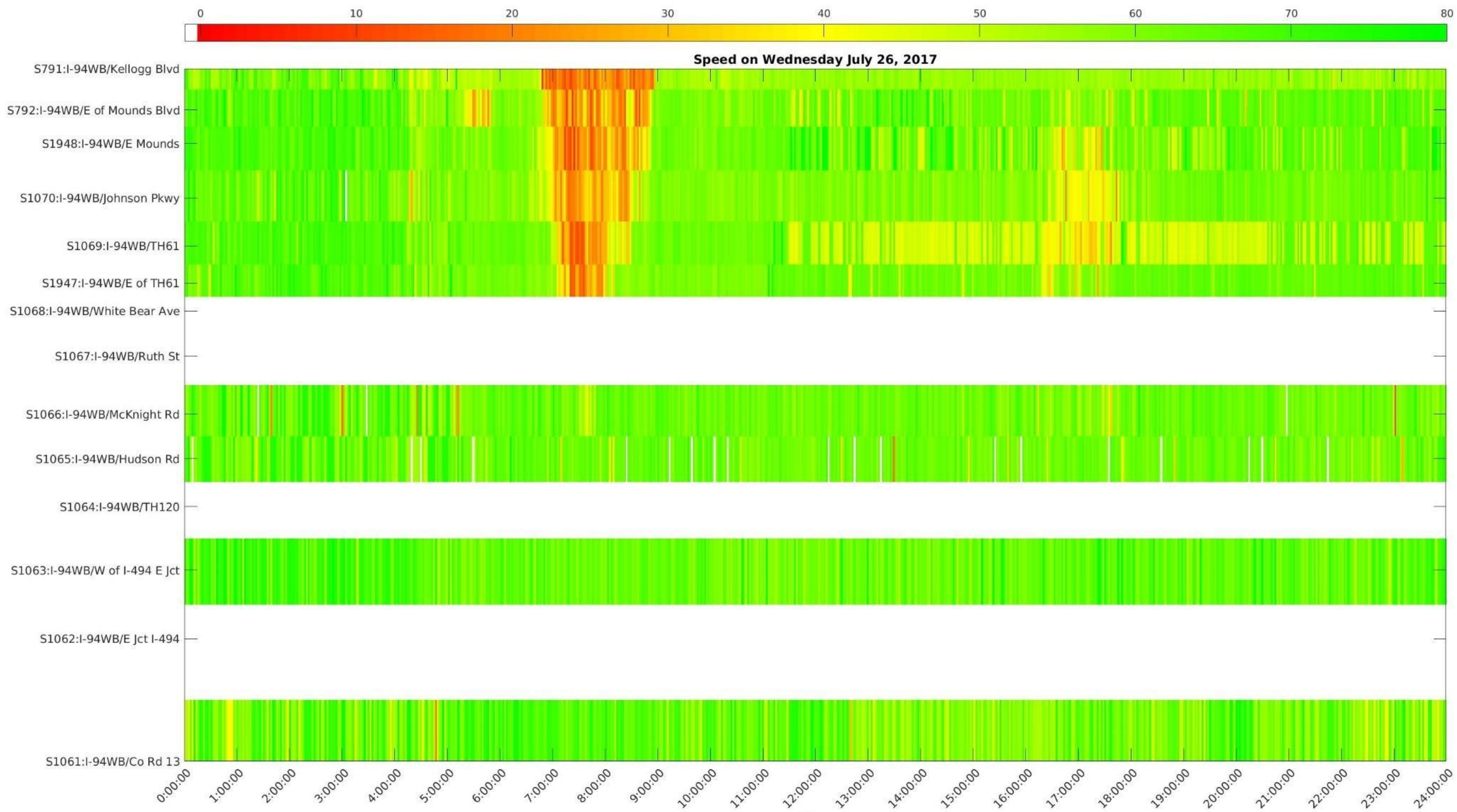


Figure 3.4 Sample heatmap showing average speed on July 26th, 2017 at each station.

The resulting heatmaps show the progression and recession of congestion. In the sample heatmap, significant congestion is first evident in the corridor around 6:45 a.m. at the Kellogg Blvd station. The congestion continues to spread upstream, reaching as far as the McKnight Rd station around 7:45 a.m., before receding beyond the Kellogg Blvd station by 9:00 a.m.

3.2.3 Sign Message Logs

The Portable Changeable Message Sign (PCMS) message logs for the six PCMS trailers that were part of the SWZSNS were imported into the analysis database from the MnDOT DMS (Dynamic Message Sign) log exported from MnDOT's PostgreSQL database. In the MnDOT database, the sign logs consist of at least two events for each message displayed – an event where the message is deployed, a second event where the message is cleared, and an additional event every 255 seconds while the message continues to be displayed where the message is redeployed. This format was not conducive for use with the detector data used, so it was also translated into a new format with one event per message. In the new format, each record contains the time a message was first shown, the time that message ceased to be shown, the duration of that message (in seconds), and a code corresponding to that message.

The SWZSNS displays a warning message on a trailer if any detector up to one mile downstream is measuring a speed below 45 mph. If no speeds are below 45 mph in that area, no message is displayed. If the speed to be displayed is greater than 15 mph, the system messages have the following format:

Line 1: X MPH

Line 2: Y MILE

Line 3: AHEAD

Where X is the speed of the slowest lane (rounded to the nearest 5 mph) at the nearest downstream station that is reporting a speed that is less than 45 mph and Y is the distance from the PCMS trailer to the station where the speed displayed is being measured (rounded to the nearest half mile increment).

If the speed to be displayed is 15 mph or lower, the messages have the following format:

Line 1: STOPPED

Line 2: TRAFFIC

Line 3: Y MILE

Where Y is the distance from the PCMS trailer to the station where the speed displayed is being measured (rounded to the nearest half-mile increment).

The messages shown to drivers were overlaid on the heatmaps to show the message displayed at any given time and location. The locations of the PCMS trailers are marked by the horizontal black lines and the trailers' messages are represented by the colored bars on those lines. The color of the vertical line corresponds to the color in the legend for the upcoming speed that drivers are being warned about while the height corresponds to the distance drivers are told that the slow traffic will be encountered (short line for ½ mile, tall line for 1 mile). An example of a heatmap for July 26th, 2017 with the sign messages overlaid is shown in Figure 3.5.

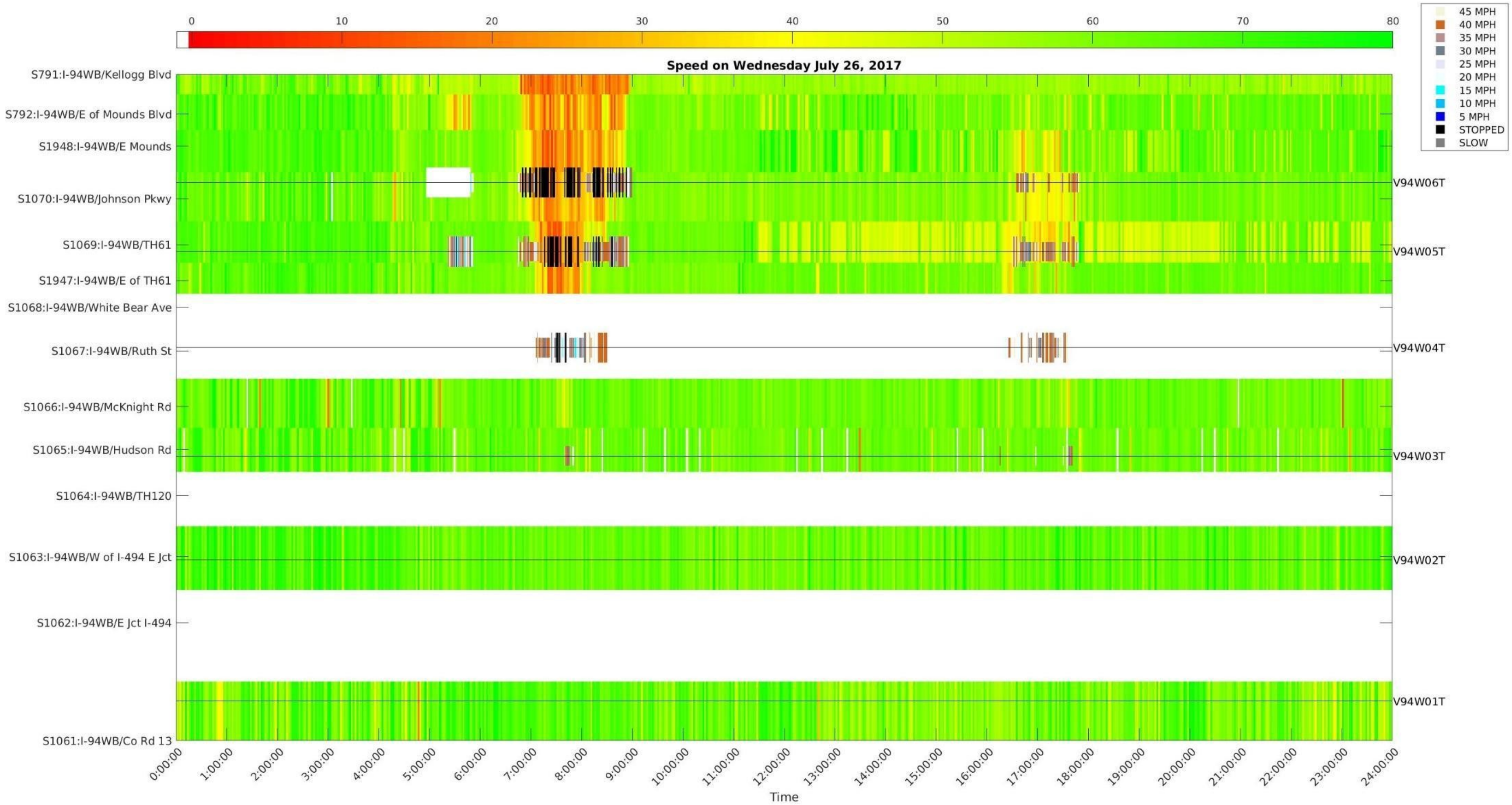


Figure 3.5 Sample heatmap showing average speed on July 26th, 2017 at each station with PCMS messages superimposed.

In the example heatmap, there appears to be an isolated slow-down event between 5:20 a.m. and 5:45 a.m. at the Mounds Blvd station that caused the SWZSNS to display "20 MPH 1 MILE AHEAD" messages at trailer V94W06T for nearly an hour and various "1 MILE AHEAD" messages at trailer V94W05T for the duration of the slow-down. The fact that both trailers, separated by roughly half a mile, are displaying messages with different speeds but the same distance ahead means that one of the trailers – likely V94W06T – is displaying the wrong distance to the slow traffic.

3.3 DATA ANALYSIS

Part of the project objectives was to monitor the SWZSN system during the first year of operation and report on its operation. The algorithm was implemented into the RTMC operations system, IRIS, by the lead programmer Mr. Doug Lau. Mr. Lau described the algorithm to the research team during project meetings but given its implementation complexity and lack of documentation, it was not possible to analyze the actual code. In the following sections, identified problems related to the systems logic are described. These problems were reported to the RTMC at the end of the first year of operation. It is unclear what actions and/or changes this feedback generated since the resulting system's operation during the final year of observation, exhibited some of this aberrant behavior but not all.

3.3.1 SWZSN algorithm configuration differences per location

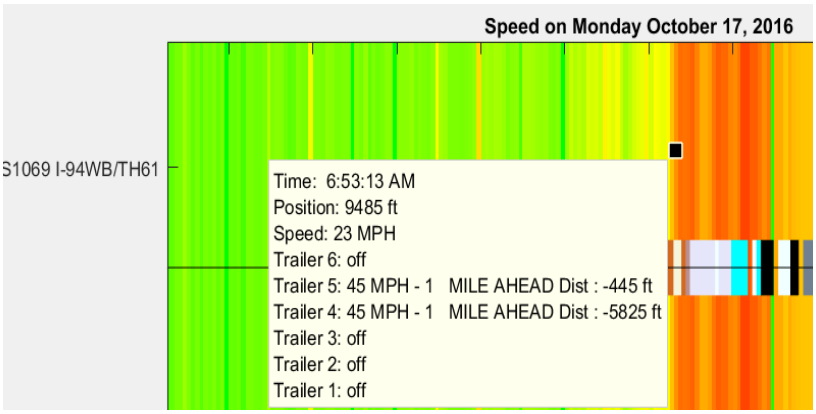
From the analysis of the data, a consistent unreasonable operation has been observed specifically on the messages displayed on SWZSN trailers 6 (Downstream of Johnson Pkwy) and 5 (upstream of TH-61). **Figure** 3.7 presents a portion of the data collected on August 23rd around 9:30am. As it can be seen in the figure the two trailers display a very low downstream speed, a condition that is not corroborated by any of the--average over all lanes--speed measurements collected. Instead, when we observed the video for this period one can notice a significant speed difference between the leftmost lane and the other two which implies that the algorithm maybe selecting a worse case lane speed to respond to instead of the average. This is contrary to the description provided by MnDOT. Separately, since the message is a general one the fact that the other lanes did not experience this speed drop could reduce the reliability of the system in the minds of the drivers on those lanes.

Regardless, according to the video records, a small shockwave generated at the level of the Earl St overpass and progressed for less than 1,000 feet before causing a three-car rear-end collision right at the location of Trailer 6 at approximately 9:29:30. As seen in **Figure** 3.7, the two trailers had started displaying messages of low speeds ahead since 9:27:47, again, with the speed data not corroborating this behavior--especially for trailer 6, since downstream conditions were good. According to the description provided, trailer 6 being at the location of the crash has no reason to display any warning since the crash downstream conditions are fine. Regardless, the trailer seems to be associated with the sensor located upstream of it on Johnston Pkwy, which is also the location of the MTO camera.

According to both the sensor data as well as the video from the MTO cameras, the congestion caused by the crash travels upstream and reaches the TH-61 sensor in less than 4 minutes. At about that time trailer 6 displays "Stopped Traffic Ahead" although again traffic downstream of the trailer is flowing with speeds above 50mph. An additional 5 minutes later, 9 minutes after congestion has reached TH-61 and moved further upstream, the trailer on TH-61 displays "Stopped Traffic Ahead".

In summary, from this example but also from several other cases, we hypothesize that either the algorithm is working is some completely different way than the one described, or the configuration in regards to these two trailers had been setup wrong. Their messages generated suggest that both the Johnston trailer and the TH-61 trailers are associated with the detector upstream of their location instead on the first downstream one in addition to having a response delay of about 2 minutes.

This hypothesis is also corroborated by the evidence provided by the next upstream trailer pair (4 and 3) as seen in **Figure** 3.8. In those cases, albeit of a delay between 2-4 minutes, the warning is displayed at the correct place and seems to be generated in association with the correct sensor locations. Unfortunately, this apparent error in configuration generated false and misleading messages throughout the evaluation period. The following figures present examples of such cases.



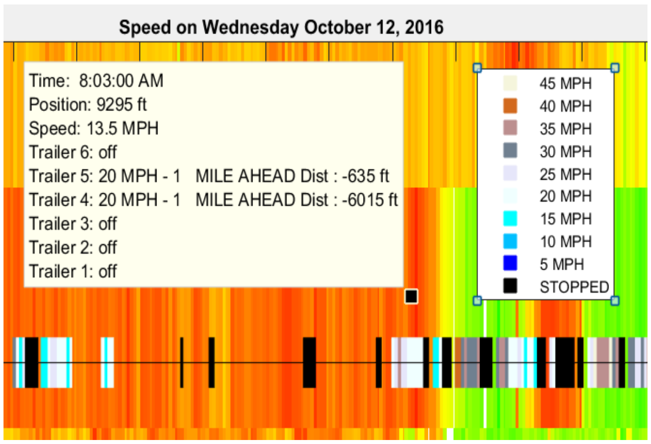


Figure 3.6 Examples where the wrong configuration generated unreasonable messages

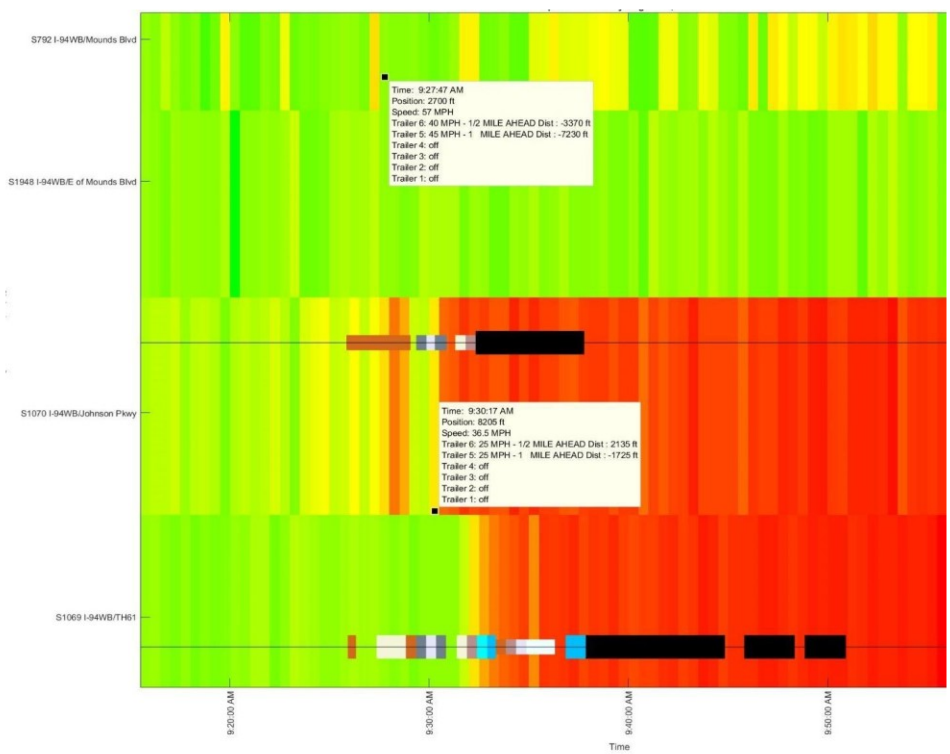


Figure 3.7 August 23, 2016 Example of unreasonable messages

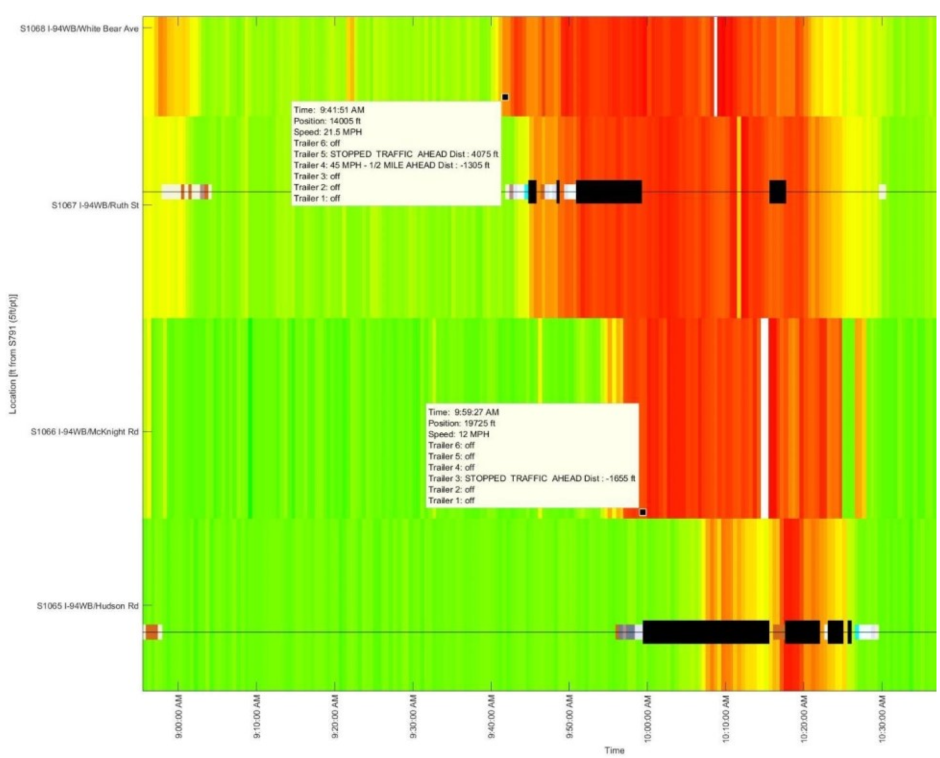


Figure 3.8 August 23, 2016 Example of reasonable messages

3.3.2 Message Timing Characteristics and Potential Issues

The second important subject in relation to the SWZSN algorithm's operation has to do with the timing of the messages generated. With the little information we have about the inner workings of the algorithm, it seems that a simple approach to congestion propagation is followed. There are no evidence of estimation of the queue spread between sensor stations although it does show signs of some smoothing in time and interpolation in space. The result of this naïve treatment of traffic flow theory principles can generate unpredictably contradicting messages out of place or time and reduce the value of the information in the minds of daily drivers.

3.3.2.1 Counterproductive use of "Stop Traffic Ahead"

Starting with the simplest example of such counterproductive operation, the method and rules the "Stop Traffic Ahead" message are evaluated in this section. From the algorithm logic description we received from MnDOT, this message was supposed to display the distance to the stopped traffic but the message log from IRIS does not show such messages having the third line in the VMS be the word "Ahead". Using again the examples presented in **Figure** 3.7 and **Figure** 3.8 we see that the sign remains active even when the traffic is stop-and-go at and upstream of its location. For example, the following picture **Figure** 3.9 is a snapshot of the traffic at TH-61 where speeds at this location as well on the upstream detector were consistently below 10mph and the VMS trailer displayed "Stop Traffic Ahead" for at least 10 more minutes.

Figure 3.9 Conditions on TH-61 while VMS displayed "Stop Traffic Ahead"

This behavior is consisted over the entire evaluation period as well as on all trailers so it does not seem to be a configuration issue like the earlier one but an issue with the algorithm logic.

3.3.2.2 Message Delay and Algorithm Logic Association Issues

Throughout the evaluation period, it was observed that the VMS messages generated have a variable delay in their correlation with the associated speeds at the downstream sensor locations. **Figure** 3.10 presents an example of this issue. Trailer #4 (V90W04T) located at the Ruth St Interchange is shown in that figure. This trailer did not present any evidence that is associated with the wrong sensors and seems to be generating messages based on some combination of data retrieved from the sensors west and east of TH-61 and the sensor on White Bear Ave (S1069, S1947, S1068). The time displayed on the top data point is the time of the last sensor record containing a speed of less than 20mph; speeds were below 20mph for 2 minutes before this point. We see that the VMS generates the first "15mph – 1 Mile Ahead" message more than 2 minutes later while the speed at half-mile distance has dropped below 35mph. VMS trailer #4 a few minutes later displays a "25mph – 1 Mile Ahead" while the speed is already at that level at about half-mile distance. The data point distances displayed are the distances between each trailer and the cursor, positive if downstream, negative if the trailer is upstream.

There are evidence of some sort of interpolation between measurements of successive downstream speeds but it is unclear if this takes place on a lane-by-lane basis or at the station level. From **Figure** 3-10 again we can observe that a short duration "Stop Traffic Ahead" is generated at 07:03:18 while the last brief period where more than a mile downstream the speed was below 15mph ended at 07:02:32. This message stays on until 07:04:50. During that time speed, half-mile downstream was below 35mph for a considerable length of time.
Without more detailed description of the inner workings of the algorithm it is not productive to speculate further what can be the reason for these discrepancies or how they can be fixed/improved.

3.3.2.3 Inconsistent Behavior of Trailer 2 (I-494, V94W0T)

In the example shown in **Figure** 3.11 an inconsistent behavior of the algorithm is observed in respect to the messages displayed on the VMS trailer west of I-494. As mentioned earlier sensor S1064 located on the TH-120 interchange had calibration issues for the majority of the evaluation period. Regardless, it seems that the sensor was underestimating speed during uncongested conditions but during congestion at least superficially seems to provide legitimate measurements. Naturally, we can only speculate if the algorithm is using this sensor or not but the issues described here seem unrelated to this part. Specifically, the messages displayed on trailer 2 don't agree with any of the immediately downstream sensors ½ or 1 mile away. As seen in the figure, even if we account for the delay described earlier the displayed messages are very different from the conditions measured by the sensors. In the example, the message is "25mph – 1 Mile Ahead" but speeds are below 20mph consistently ½ away to at least 1.5 miles downstream. Separately, trailer 2 never displays a "Stop Traffic Ahead" message even when conditions clearly justify it but it turns off, as it should when congestion reaches its location in difference to most of the other trailers. Again, we can only point out the discrepancy but cannot hypothesize on the reason behind it.

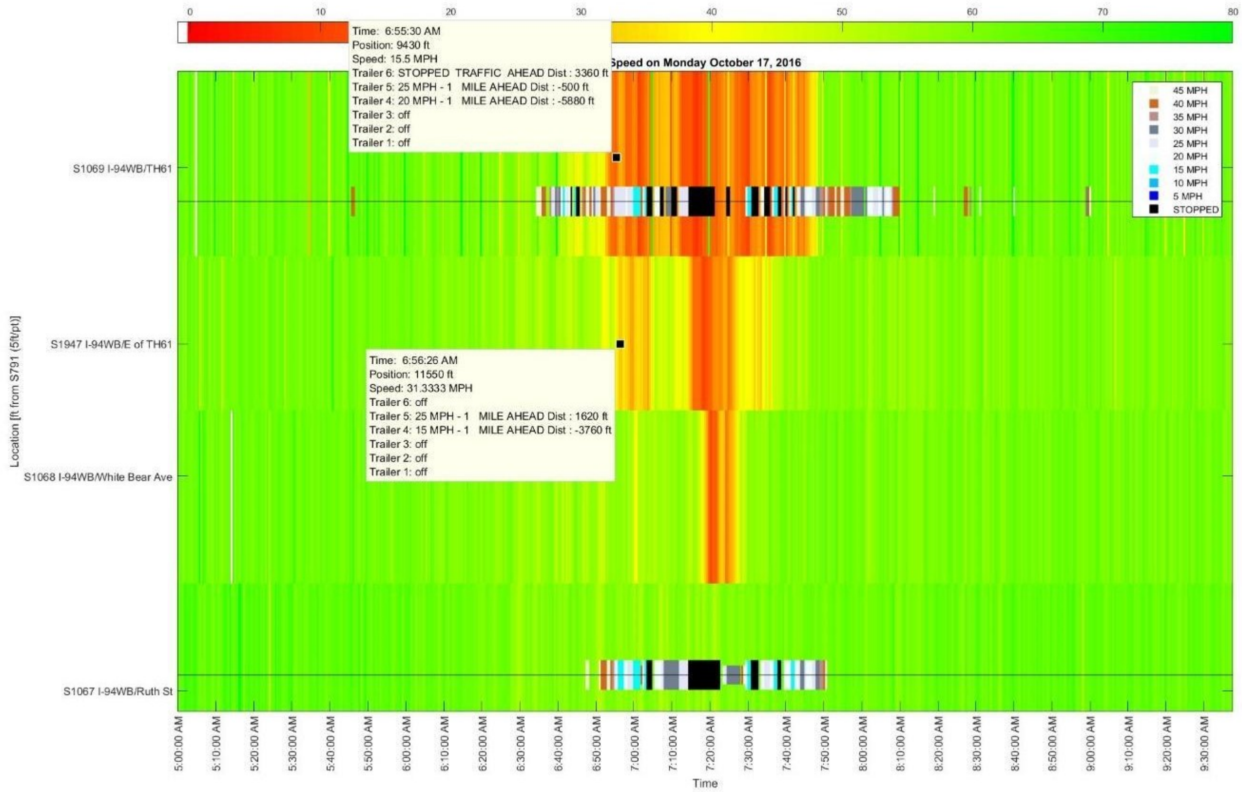


Figure 3.10 Example of message delay and missed warning

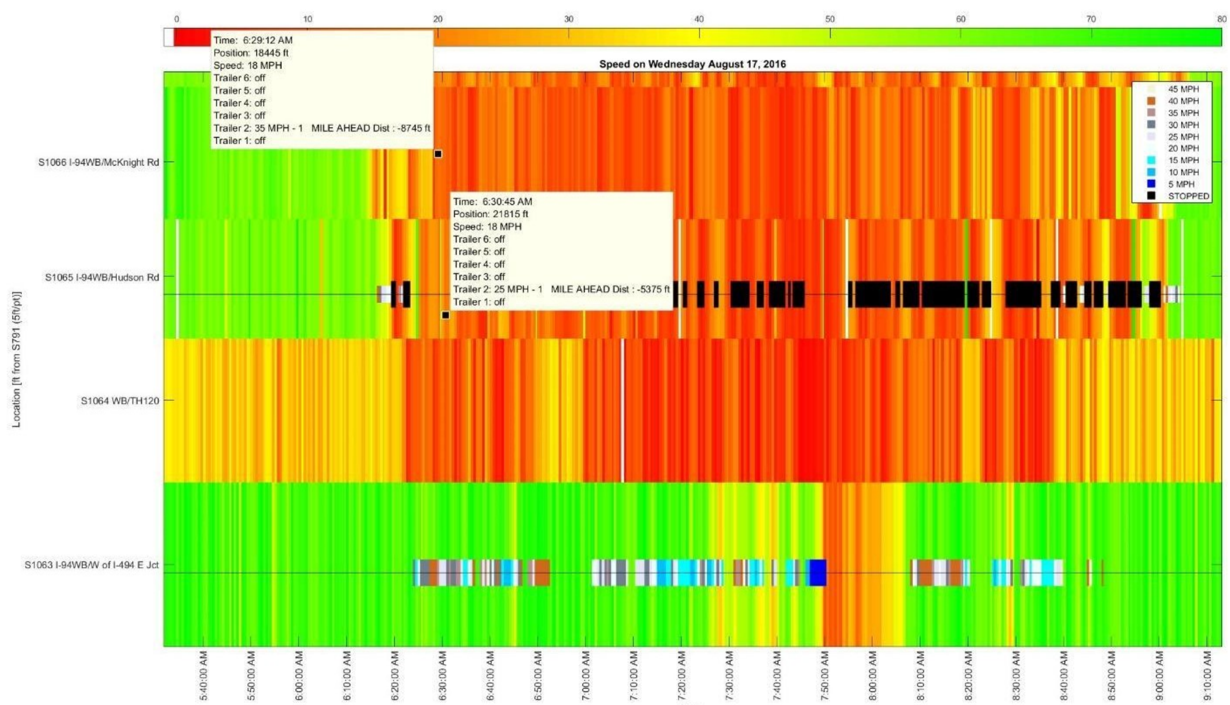


Figure 3.11 Example of Unclear behavior of Trailer 2 (I-494, V94W0T)

3.3.3 SWZSN Congestion Spread Delay

From closer analysis of all the days, the SWZSN system was in operation, evidence of delaying the spread of the congestion have been collected. In general, it seems that when the system displays informative messages at the proper time, meaning messages describing an actual large speed drop between the sign location and downstream conditions, the upstream progression of congestion is halted for considerable periods. **Figure** 3.12 presents a collection four examples where this behavior was observed. The first three all show a break in the congestion progression, while the last two (side by side) present a day where there is evidence of congestion delay (left) and a day without the SWZSN where the familiar congestion progression can be seen (right). The reason for such a delay may be the selected, more gradual deceleration of the vehicles as they approach the back of the queue in a way that allows them to achieve higher densities without lowering their overall speed. Naturally, given the demand level, compressed or not eventually the higher densities will cause a speed reduction so the result is a congestion delay instead of a congestion avoidance.

In the introduction of the results earlier in this document, we referred to this effect as shockwave elimination. The reasoning behind this terminology is because congestion is progressing upstream through a series of shockwaves, each contributing to the streams instability and eventual breakdown. Uniform traffic made up of attentive drivers with normally short reaction times may operate as a dumper to the shockwave trajectory, eliminating a large number of them and retaining the streams stability. These observations are encouraging since they show that the SWZSN system may be having an observable influence on driver behavior. In Chapter 5 were the trajectory analysis is presented, this effect is indeed highlighted.

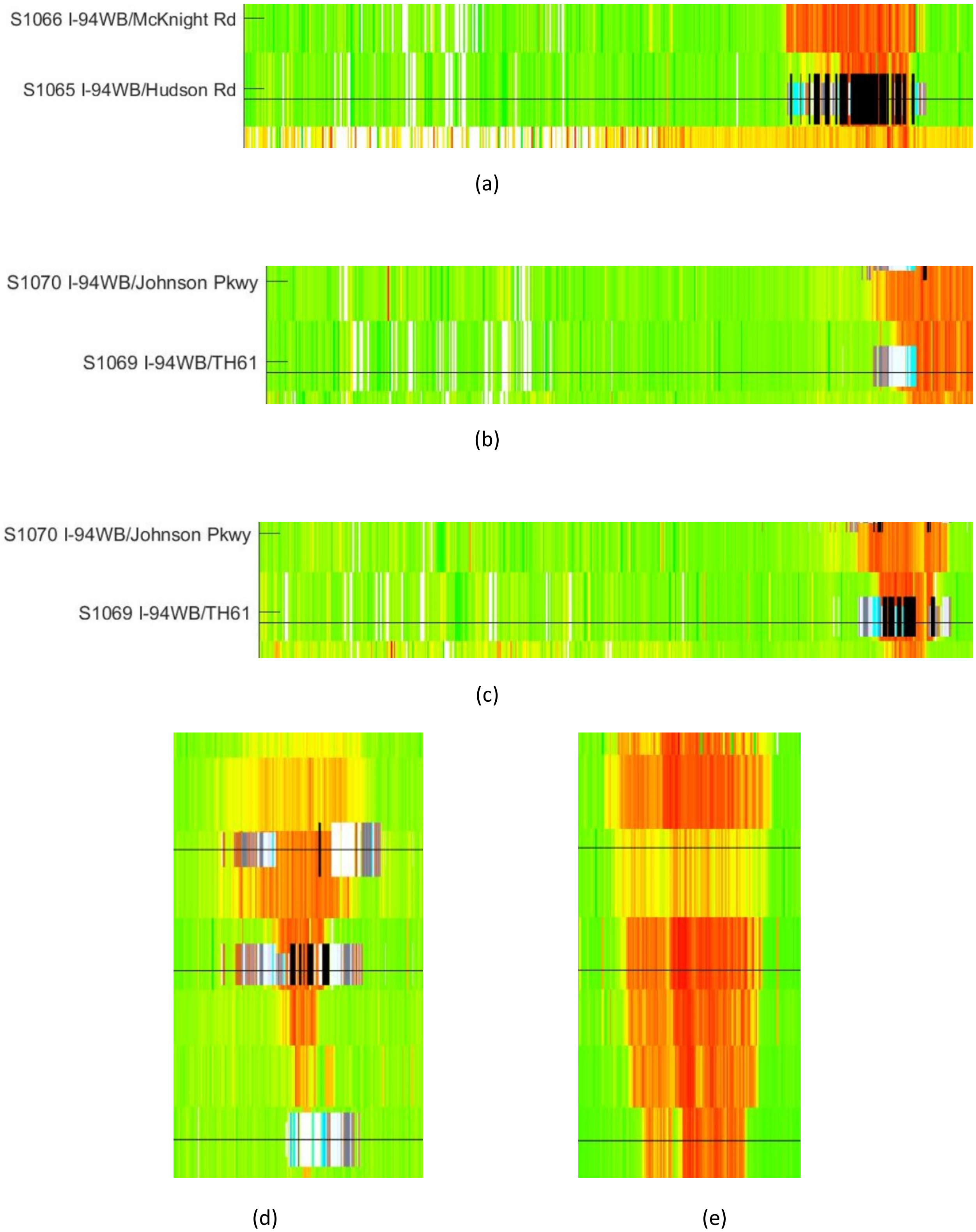


Figure 3.12 Evidence of Delaying the Spread of Congestion

3.3.4 Trajectory Extraction Investigation

To help prepare for the 2017 construction season, a feasibility investigation was conducted with the trajectory extraction tool to determine if the video collected would be suitable for the needs of the project. The TET, which is described in more detail in 4, requires a set of configuration files that are specific to the camera view and must be fine-tuned to optimize the extraction for the movement in the scene. The initial investigation using the 2016 data consisted of manually creating these configurations for each camera, running the extraction on a set of video, and inspecting the results.

This investigation resulted in a few important findings. For one, the positioning of the cameras was not ideal in most cases and in some cases essentially unusable. This led researchers to raise the cameras higher on the poles for the 2017 data collection to provide a more optimal view of traffic, as described in 2. In addition to this, the process of manually calibrating the trajectory extraction configuration was determined to be too difficult given the amount of data that needed to be analyzed. Much of this stemmed from the type of movement exhibited by freeway traffic, which caused issues with the accuracy of the resulting data due to the underlying heuristic algorithms used by the tool. This problem, which is discussed in more detail in 4, led researchers to develop an automated calibration tool that could find a more optimal configuration for the tool without requiring as much manual effort.

Finally, the methodology used in this investigation involved running the trajectory extraction on all video collected over a period of time, then using the resulting trajectory data to identify congested conditions with queueing for further analysis. This methodology proved to be very time consuming, in that trajectories would need to be extracted for an entire day of video to obtain less than an hour of data with the conditions of interest. This led to a modification of the methodology used to extract data for analysis that used undergraduate research assistants to scan through the video quickly and obtain time periods that showed the kind of traffic conditions that were useful for analysis. This reduced the computing time needed to extract the trajectory data for analysis, accelerating the data reduction process and allowing more time to be spent on analysis of the data.

In all, this investigation proved to be a useful exercise that allowed researchers to better direct their efforts in the 2017 season data collection, reduction, and analysis. The analysis that was ultimately conducted using this data is presented in detail in the following chapter.

CHAPTER 4: POST-SYSTEM DEPLOYMENT (PHASE II) DATA REDUCTION AND PROCESSING

To distil the relevant data from the hundreds of hours of video collected, the videos that would likely show queuing vehicles were manually scanned to note whether the videos showed queuing and, if so, the times that the back of a growing queue was visible. Clips of the times showing the back of a queue were made and all vehicle trajectories were extracted using a custom Trajectory Extraction Tool (TET). The trajectories corresponding to decelerating vehicles were then cleaned of noise, and a deceleration rate was fitted to them. To match the analysis performed in the previous project phase, the aforementioned records were also used to produce a queue frequency plot for 2017.

4.1 QUEUE FREQUENCY SUMMARY

To show present the results in a similar fashion to the queue location summary for the 2016 data collection, a tool was created to combine several heatmaps and produce a gradient of queue frequency for each time and location. This new queue location summary is broken down by detector station instead of camera view region and includes the locations of the PCMS trailers. To show the “normal” queue locations, the queue location plots of 20 average days were combined to form the queue frequency summary plot. The resulting queue frequency plot is shown in **Figure** 4.1. The days used were selected by comparing each day’s total volume entering and the fluctuations of the entering volume throughout the day. This helped to control for variations in the number of vehicles on the road at any given time from day to day. This process took a research engineer approximately 10 hours over the course of two weeks.

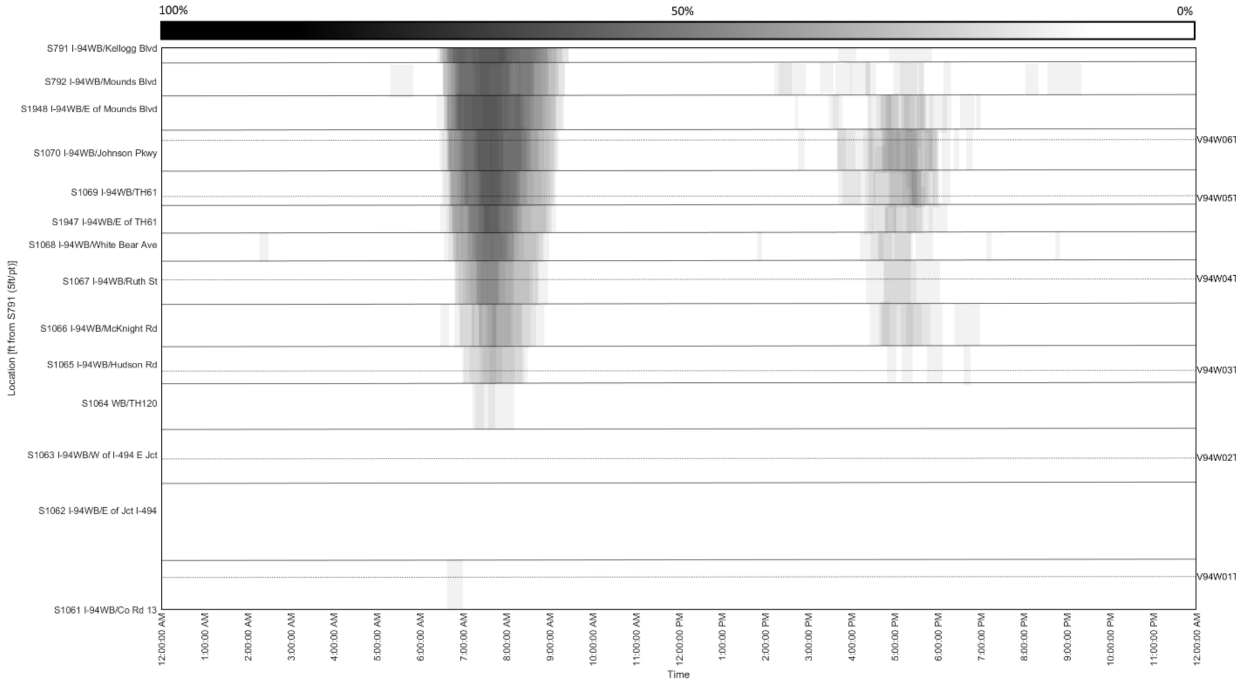


Figure 4.1 Queue frequency by location and time based on 20 normal days

Similar to the conditions observed in 2016, queuing is most frequent in the morning between 6:30 a.m. and 9:30 a.m. (i.e., the morning peak) with some scattered queuing in the afternoon between 3:00 p.m. and 7:00 p.m. (i.e., the afternoon peak). The queue frequency plot shows that queuing generally extends up to McKnight Rd, but sometimes it can travel as far upstream as TH-120/Century Ave.

4.2 VIDEO DATA REDUCTION

Vehicle deceleration rate was selected as a surrogate measure of driver surprise when encountering slow or stopped traffic based on the assumption that drivers brake harder when encountering the back of a queue because they did not have enough advance notice to decelerate more gradually. Vehicle trajectories composed of position and velocity can be collected using video data, but the vehicles for which trajectories are being extracted must be selected with some care. The number of trajectories must be limited in part because trajectory extraction is processing-intensive, thereby making the proposition of extracting all vehicle's trajectories infeasible and inefficient; also, picking out the trajectories of vehicles that actually encountered a queue with in the frame of view of a camera is a very time-consuming process. To more effectively exclude irrelevant vehicles from the dataset, the portions of the video data that did not show vehicles meeting the back of a queue were screened out before the trajectory extraction process.

4.2.1 Screening for Visible Backs of Queue

The screening process consisted of three passes of the video data, each with increasing scrutiny. The first step in the selection process involved scanning through the message database for the entire evaluation period and excluding any days that had messages that warned of crashes, stalled vehicles, or debris on the road because those days are unlikely to be representative of normal driver behavior and traffic patterns. Weekends and holidays were also excluded from the analysis for the same reasons. The number of videos to be scanned was further reduced by selecting days and times that had a high potential for containing footage of queuing. This was done by looking through the heatmaps of the days that had not been excluded and selecting dates and time ranges that showed congestion near each of the camera stations. A list of videos to consider in the next steps of the selection process by cross-referencing the list of dates and times selected for each camera with the video availability for those dates, times, and cameras.

The second step of the selection process consisted of quickly scanning through the videos selected in the previous step and noting whether the video showed queuing in the westbound lanes and if the video was useable for trajectory extraction. Some videos were not considered useable for trajectory extraction as they did not adequately show the traffic. Reasons for considering a video unusable included file corruption, rain or debris covering the lens, or improper aiming (either because of mechanical failure of the camera mount or because the roadway alignment was shifted out of the frame of view of the camera). The result of this step was a list of videos that showed queuing – though not necessarily the back of a queue.

In the final step of the screening process, videos that were found to show queuing were then carefully inspected and any times that contained footage of vehicles approaching the back of a queue were then recorded and used create clips showing vehicles approaching the back of a queue. Because determining the location of the back of a queue is quite subjective, the bounds for each clip were expanded beyond the times recorded by one minute before and after. These buffered bounds for the clips helped ensure that all of the vehicles approaching the back of the queue are included. These clips make up the input for the trajectory extraction process. Overall, this screening process took a team of undergraduate research assistants approximately 280 hours of effort expended over the course of three months, with an additional 80 hours spent by a research engineer managing the team.

4.2.2 Unique Views and Layouts

Throughout the course of the evaluation period the road conditions changed frequently–in the form of the daily shifting of moveable barriers, changing of striping, placement and removal of cones or barrels, or the closure of lanes. While less frequent, shifts of the cameras occurred too–both intentional shifts to better capture traffic and unintentional shifts caused by the elements. The videos from each camera station that shared the same combination of different road conditions and camera positions were grouped together to form “views.” Similarly, the views were grouped by road conditions, both in terms of geometry (lane location, number, and width) and delineator type (concrete barriers, cones, barrels, or nothing) to form “layouts”. Videos from the same layout share the same road conditions but the camera positon may vary between videos. These groupings make it possible to take road conditions into account when looking at the effects of the SWZSNS–differences in road geometry could potentially impact drivers’ behavior. The process of identifying these views and layouts took an undergraduate research assistant approximately 10 hours over the course of one week.

4.2.3 Trajectory Extraction

Extraction of trajectory data from video was done using a Trajectory Extraction Tool (TET) largely based on the open-source computer vision program *TrafficIntelligence* (Jackson et. al, 2013), developed by Dr. Nicolas Saunier at Polytechnique Montreal, which itself is based on the OpenCV library. This program was designed with traffic applications in mind which helps to simplify the process of configuring and calibrating the tracking system, allowing users to spend more time on their particular application. The main configuration step required to use this program with a particular set of video footage is the generation of a homography: a matrix for projecting the coordinates of objects from the perspective of the camera to world space. This step requires an aerial image of known scale (from Google Maps or similar) and a sample camera frame. The user must then select corresponding points in the two images, from which the system calculates the optimal homography that minimizes the total error of the projected points. An example of the points used for generating a homography for one of the sites can be seen in **Figure** 4.2.

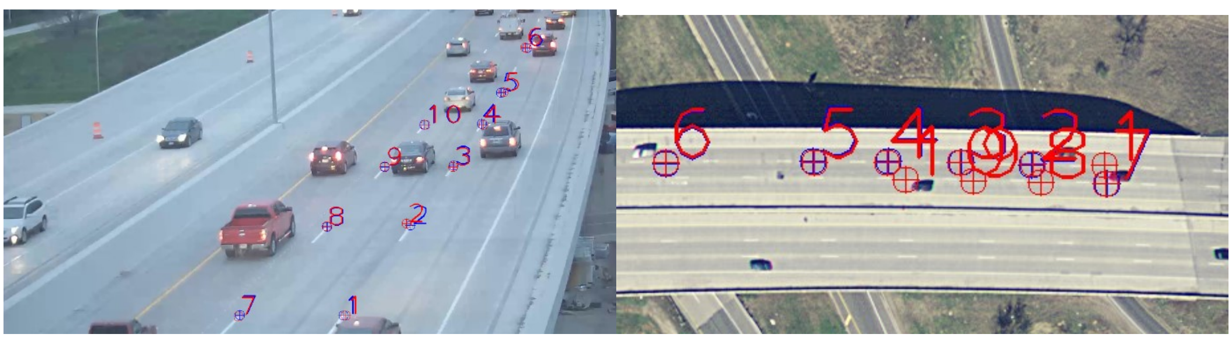


Figure 4.2 Example of points used to generate the homography for one of the TH-61 layouts. The left image is the camera frame, and the right image is the aerial image. On each image, the blue points are the original points selected on that image, while the red points are the corresponding points projected from the other image using the computed homography.

The methodology used by TrafficIntelligence to extract trajectories from video uses two passes to generate object trajectories at the level of road users (i.e. vehicles) from the low-level “features” (small details made by the corners and edges of objects such as wheels, mirrors, doors, etc.) that are tracked by the underlying image processing algorithm. This methodology is based mostly on heuristics that use the speed and density of features relative to one another to filter out slow moving objects and group the strongest targets in the image. This behavior can be influenced by adjusting one or more thresholds, however depending on the scene observed, it is not always easy to find values that account for all errors that can be made by the system, leaving the user with vehicles that have been erroneously grouped together (over-grouping) or individual vehicles represented by multiple trajectories (under-grouping). To help eliminate the inclusion of extraneous features such as moving trees, vehicles on other roads, or other objects in the background, the regions of the camera frame that are considered when identifying features are restricted to the regions where relevant vehicles will be. This is done by creating a "mask image" that covers up any irrelevant regions of the camera frame.

Because the projection of the coordinates from the camera view to the world view and the masking of regions of the camera frame are dependent on position and orientation of the camera, a new homography and mask must be made for each significant change in camera orientation. In addition to this, a new homography and mask must be made when the layout of the road changes significantly, which occurred several times over the course of data collection, due to changes of the position in the frame of the vehicles of interest. Ultimately configurations were made for 37 separate camera views that were processed, taking a research engineer approximately 120 hours of effort over the course of 4 weeks.

Using the homography and mask for a given view, the TET is run for a clip that shows representative lighting and traffic conditions. This initial run of the TET is done using the default configuration and produces rough feature groupings based on those default parameters. Any issues in the resulting groupings in the clips are then manually corrected; over-grouped features are split up into the correct number of objects and under-grouped features are grouped together into single objects. This corrected data set is then used as a target to generate an optimal configuration using an automated optimization routine based on a genetic algorithm and the CLEAR MOT tracking accuracy measures (Bernardin and Stiefelhagen, 2008). In all subsequent runs of the TET, this optimal configuration is used as the configuration for that view. While there are limitations to this process that result from the inability to improve the data beyond what the initial feature tracking run achieved, starting with an initial data set speeds up the process considerably compared to manually labelling an entire video frame by frame, allowing more camera views and layouts to be processed in less time. Despite this time reduction, the annotation process still took a team of undergraduate research assistants approximately 160 hours of effort over the course of 4 weeks. The development of the software to perform the optimization process using this data took an undergraduate programmer approximately 140 hours of effort over the course of 6 months.

Initially, during the course of generating trajectory data using this method, a unique optimal grouping configuration was created for each camera view and road layout. After some testing, however, it was determined that video from one camera view and road layout could use the optimized grouping configuration from a similar set of video. In this case, videos were considered similar enough to use the same configuration if the vehicles of interest were located in roughly the same region of the camera frame and were roughly the same size in the image, since the grouping parameters would be applied to features with motion that was numerically similar in the two data sets. This simplification was confirmed as valid by comparing the accuracy of trajectories extracted with the different configurations to a set of manually-corrected data. In cases where the views were similar, this resulting accuracy was close to that of the result obtained using a uniquely optimal configuration. An example of two camera views/layouts that were considered similar is shown in **Figure** 4.3.

Figure 4.3 Example of two camera views/layouts that were considered similar enough to use the same configuration. In this case, the error from using the optimal configuration from one view on the other was approximately 7% compared to using the uniquely optimal configuration.

Once the target groupings are created, the TET can be run on all clips for a given view. The results of each run of the TET are saved in a large SQLite database containing feature trajectories and the object trajectories those features are grouped to form. The object-level data is then moved to PostgreSQL database tables made up of summary records containing an object's trajectory and the corresponding date, camera, view, layout, system status (active or inactive). A more detailed set of records for each object contains the position and speed of the object, the lane that the object was in, and the feature bounds for every frame in which that object was identified. Because the TET takes a comparatively long time to run (on the order of several minutes to a few hours, depending on the length of the video and the amount of movement in the scene) a custom processing system was developed to allow using multiple computers to run the trajectory extraction software on multiple videos simultaneously while accounting for bottlenecks such as hard disk read times. This system relies on a custom file management system that was developed to allow collecting information about large numbers of video files in a PostgreSQL database. Together these tools allow for better organization of video and configuration files and dramatically reduced run times when processing large numbers of videos. The development of these tools, which took place between construction seasons in early 2017 while the trajectory-based analysis methods were being refined, took a research engineer approximately 120 hours over the course of two months.

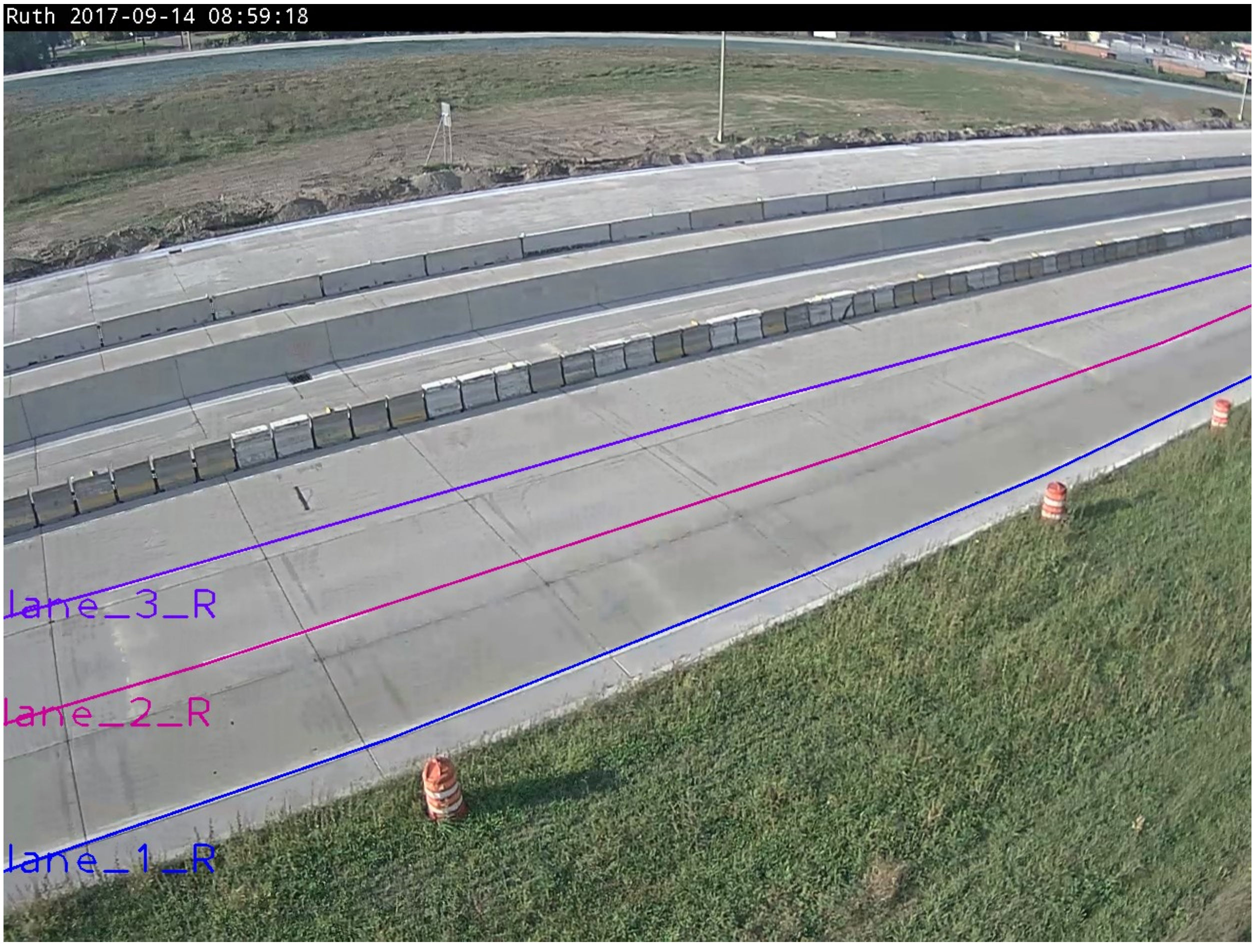


Figure 4.4 Example of lanes defined in a camera viewing vehicles from the right, where the right lane markers are defined.

Due to error introduced from the positioning of the camera and the height of vehicles, which can make it appear that vehicles are in more than one lane at any given point, the method for selecting the lane of each vehicle used lines drawn on the lane markers in the camera frame labeled with the lane number (with 1 as the rightmost lane) and the side of the lane that was defined. When cameras viewed vehicles from the right side (based on the direction of travel), the lane markers on the right side of the vehicles were defined (as in **Figure** 4.4); when vehicles were viewed from the left side, the lane markers on the left side of the vehicles were defined. Vehicles were then assigned a lane by choosing the first line from the bottom of the image that the vehicle was "mostly" above. This prevented vehicles from being placed into a lane because of their height made them appear to be in that lane, while also preventing shadows from making a vehicle appear to be in the incorrect lane. This capability was developed and added to the existing processing system by a research engineer, taking approximately 40 hours of effort over the course of one week.

4.2.4 Vehicle Association with Message Records

Once trajectories were extracted from video and imported into the PostgreSQL database, the individual vehicles observed were associated with the message records in the database using a back-tracking algorithm that employed MnDOT detector data to estimate a trajectory for the vehicle moving through the corridor. To calculate the travel time between points along the corridor, the space between each pair of detector stations was split into three segments. In the downstream-most segment, the 30-second speed from the downstream station was used to calculate travel time across the segment, and in the upstream-most segment, the speed from the upstream station was used to calculate travel time. In the middle segment, the speed at the two stations was averaged together to calculate the travel time. The maximum speed value from the individual detectors was used as the speed at each station.

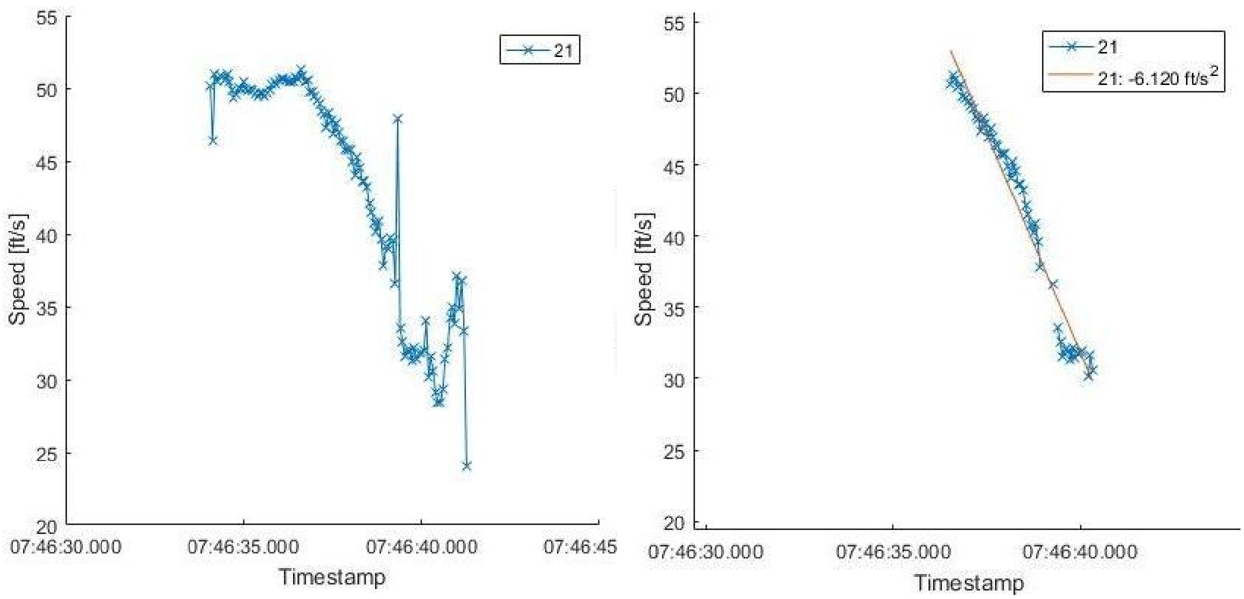
This algorithm started with the linear position of each vehicle along the corridor at a given date and time, then used the aforementioned methodology to estimate travel time along each segment, moving backwards through 30-second intervals as necessary until it reached the beginning of the work zone. This corridor trajectory was then used to estimate the time when that vehicle was next to each message sign, and the corresponding message record was recorded in the database for that sample. In cases where the camera was upstream of some of the trailers, the messages for the downstream trailers were set to NULL, since that vehicle would not have seen that sign yet at that point. In cases where the vehicle would have passed by the sign but the sign was blank, the message was set explicitly to “BLANK.” The implementation of this algorithm and integration into the analysis took two software engineers approximately 70 hours of combined effort over the course of 5 weeks.

While this method was suitable for this analysis given the amount of data collected, there is a limitation in that it assumes that every vehicle observed entered the corridor before the most upstream message sign. It is therefore not able to correctly handle cases where vehicles entered the freeway from one of the entrance ramps or interchanges downstream of any of the trailers, in which case they would not have seen those messages. It should be noted, however, that it would be impossible to identify these cases without true individual vehicle trajectories, which are simply not available.

4.2.5 Trajectory Selection and Fitting

Once the combinations of sign messages that each vehicle is likely to have seen before encountering the back of a queue have been determined, they are aggregated in analysis groups and assigned relative priorities for trajectory extraction based on the system status, camera, layout, and signs seen. Trajectories are only extracted for vehicles that encountered the back of a queue. In effect, this means that trajectories are selected if they begin above 30 mph, end below 30 mph, have a net speed drop of at least 10 mph, and have at least 30 points before noise is removed. The criteria that objects’ speeds must begin above 30 mph and end below 30 mph filter out cases where the vehicle was either already in a queue or never encountered a queue while it passed the camera. The criterion that speed must drop by at least 10 mph ensures that the vehicle actually decelerated in any sort of significant way.

If an object's trajectory meets the above criteria, the noisy data points are removed. An example of a trajectory before cleaning is shown in **Figure** 4.5 (a). A balance must be struck between removing noise and removing so many points that the trajectory is no longer an accurate representation of the path of the object. The same trajectory is shown in Figure 4.5 (b) after the removal of noise and a deceleration rate has been fit to the remaining points. This process of cleaning and fitting is repeated for a given analysis group until there are no more trajectories to choose from or enough samples have been selected to carry out a meaningful analysis at which point the process is repeated for the analysis group with the next highest priority.



(a) (b)

Figure 4.5 Sample of velocity vs time plot before (a) and after (b) removing noise and fitting deceleration rate

The tool developed to carry out this process was developed specifically for the project to allow for this detailed investigation into the trajectory database. The tool was written in MATLAB to leverage its included graphical user interface toolkit that simplified the process of editing data on a plot. Development of this tool started with approximately 80 hours of effort by an undergraduate programmer over the course of two months, followed by approximately 20 hours of effort by a research engineer over the course of 3 weeks. The actual cleaning process was carried out by a team of several undergraduate research assistants that spent approximately 300 hours of combined effort over the course of two months.

In addition to the manually-cleaned trajectories, statistics were added to the remaining trajectories in the database to allow a similar analysis. This consisted of adding a field for the 15th percentile speed and 85th percentile speed, along with a field that noted whether the vehicle was accelerating or decelerating. The 15th and 85th percentile speeds were used rather than the minimum and maximum to reduce the effect of noisy data on the analysis. The addition of these fields to the data, which was done using the data in the PostgreSQL database after the TET was run, took a research engineer approximately 10 hours of development time over the course of two weeks.

CHAPTER 5: FINAL DATA ANALYSIS

As described in the previous section, the final SWZSNS evaluation is based on the approximated individual vehicle decelerations as they approach and join the traffic queues visible from the camera locations. These decelerations are approximated since they are extracted from vehicle trajectories and then filtered to reduce measurement noise. Each recorded sample vehicles deceleration is also correlated with the messages this vehicle's driver was exposed to if we make the assumption that the vehicle entered the freeway more than 1.5 miles upstream of the measurement location. In addition, multiple measurements were collected in an attempt to sample traffic under different work zone geometric and traffic control conditions. The extraction of trajectory information proven to be a more difficult and expensive effort as originally anticipated so not all of the collected video was processed. Priority was given to video sequences captured during work zone conditions while the system was operating (2017) similar or of bearing close resemblance to conditions during times where the system was not yet activated (2015 and early 2016). Unfortunately, all these requirements and conditions along with the limited amount of time the corridor exhibited back-of-the-queue transitions radically reduced the amount of relevant records to be analyzed. **Figure** 5.1 presents a summary of the data finally analyzed. Each column represents the amount of samples available on each location under each of the prevailing work zone layouts. Only Johnson and TH-61 contain enough observations taken during periods of similar layouts with and without the SWZSNS operating. The rest of the locations still provide some useful information but not a direct W/WO comparison

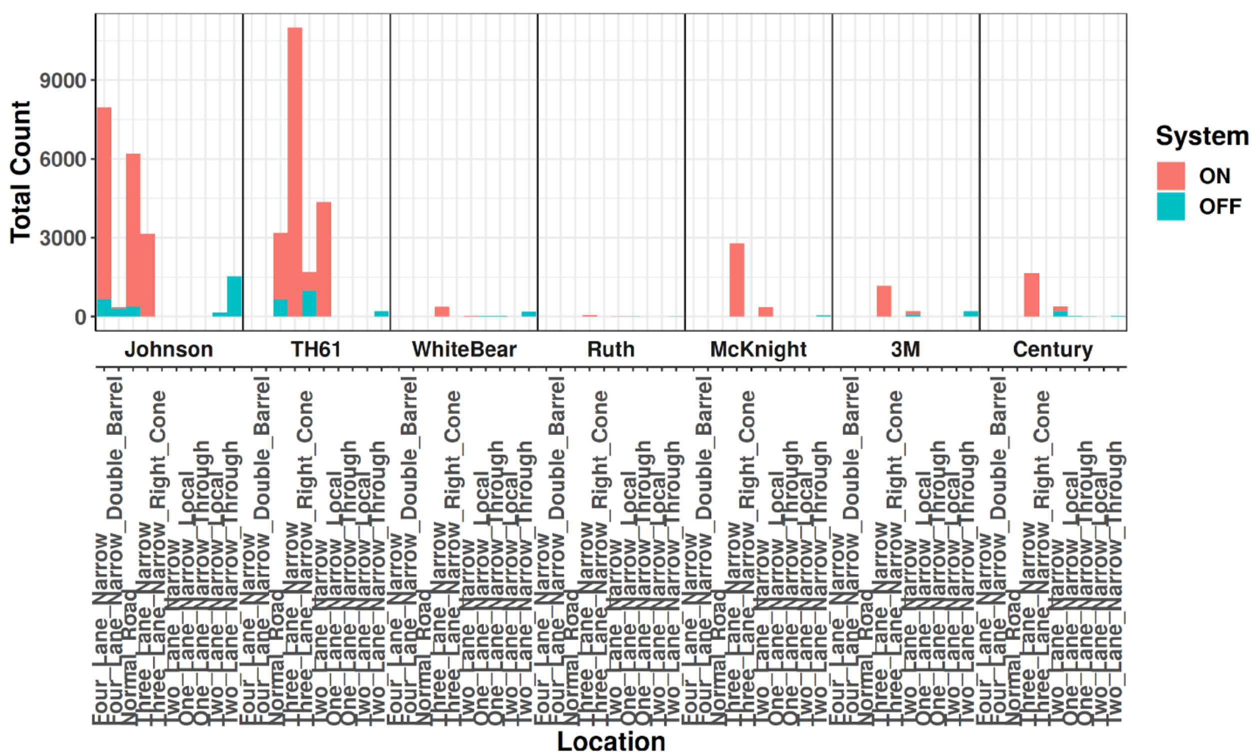


Figure 5.1 List of Available data per construction zone layout

5.1 JOHNSON PKWY STATION TRAJECTORY ANALYSIS

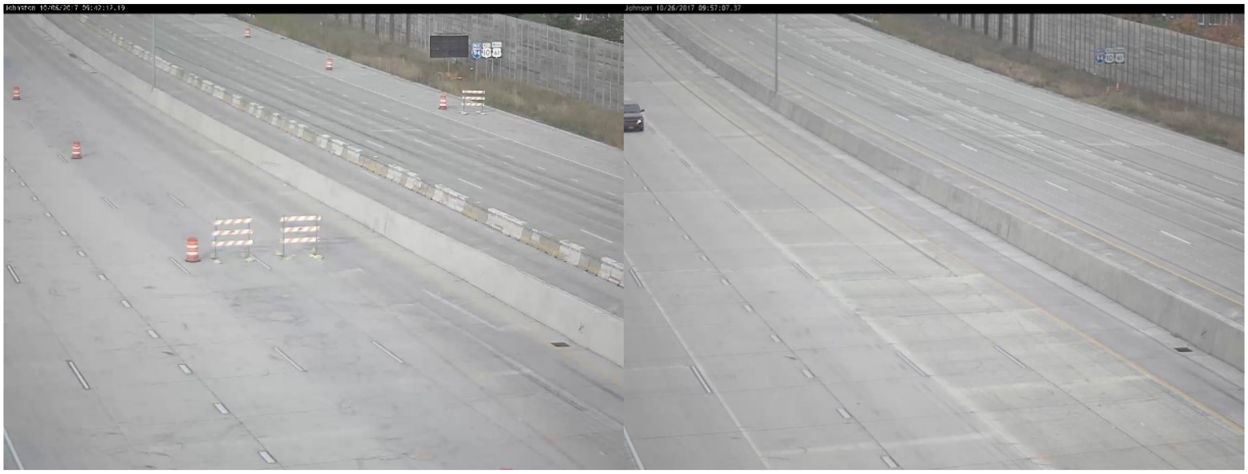


Figure 5.2 Johnson Pkwy Station. All Lanes Open Layouts. 4-Lanes No Shoulder, Normal Road

Figure 5.3 Johnson Pkwy Station. Reduced Lanes Layouts. 2-Lane Narrow Through only, 3-Lane Narrow.

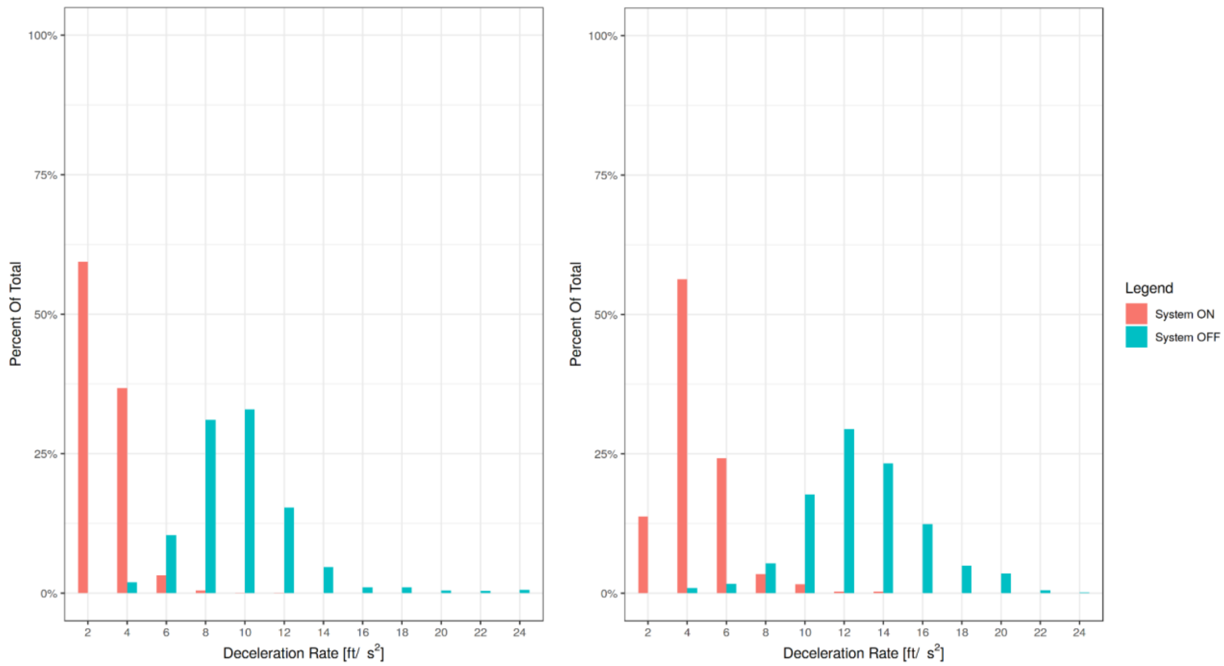


Figure 5.4 Johnson Pkwy Station. Reduced Lane Work Zone Layouts. Decelerations (Calculated, Manual)

The extracted deceleration (calculated and manual) in **Figure** 5.4show a substantial decrease of the level of decelerations with the system in place. These graphs present observations during periods of reduced lane road conditions.

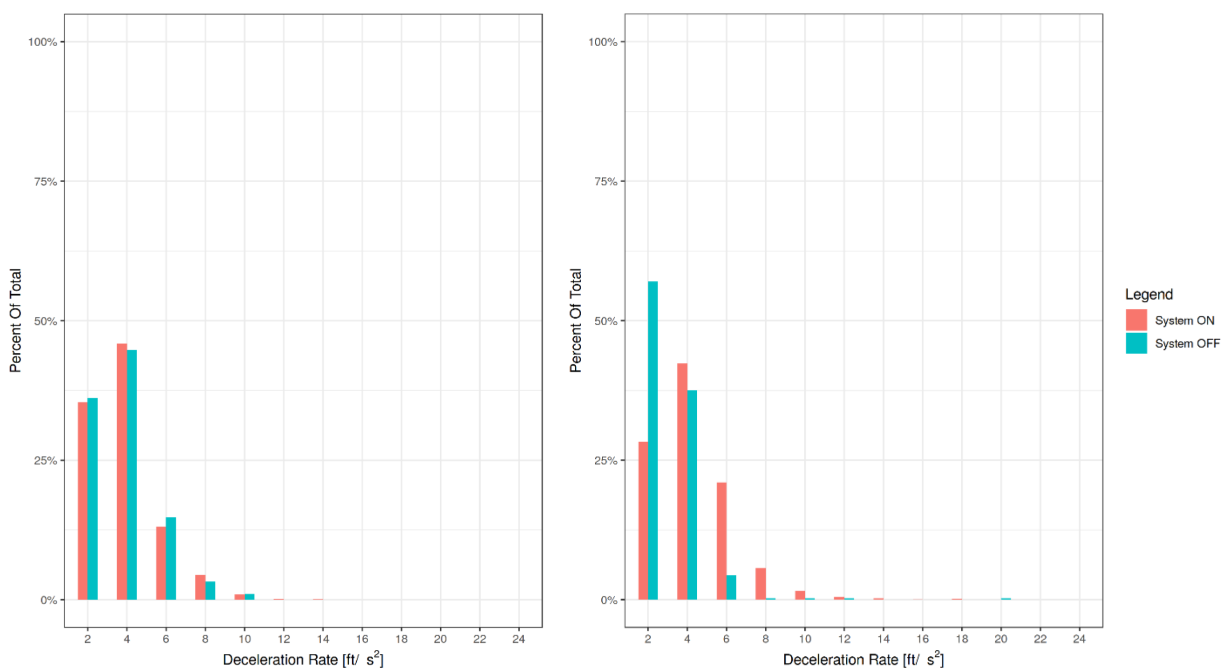


Figure 5.5 Johnson Pkwy Station. Calculated Deceleration. 4-Lanes no shoulder and Normal Road

In difference, as seen in **Figure Figure** 5.5 on periods where the road was with all four lanes available either with no shoulder or with no active work zone (Normal Road). When there is no significant capacity reduction due to the work zone the speed notification system doesn't seem to offer any benefit although there was congestion forming.

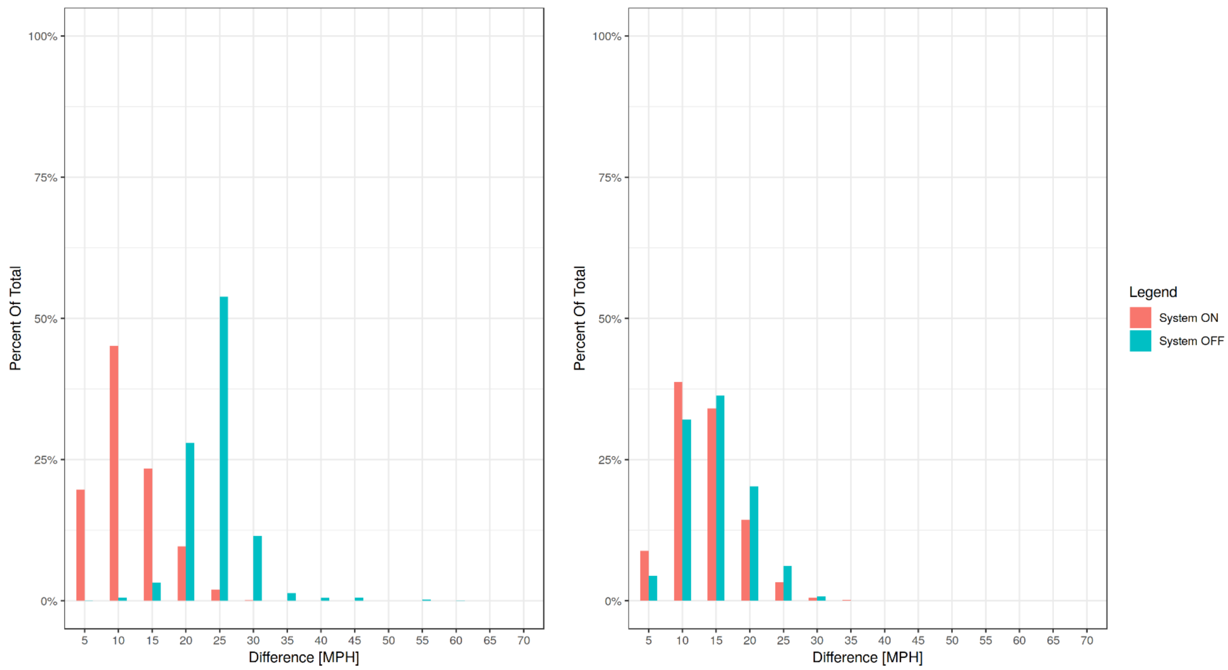


Figure 5.6 Johnson Ave Station. Speed Difference. Reduced Lanes and 4-Lane No-Shoulder

One reason for this behavior could be the fact that the difference between 15th-percentile and 85th-percentile (**Figure** 5.6) speeds was high without the system during the reduced capacity conditions while under all-lanes open conditions that difference is much lower, similar to the reduced capacity days.

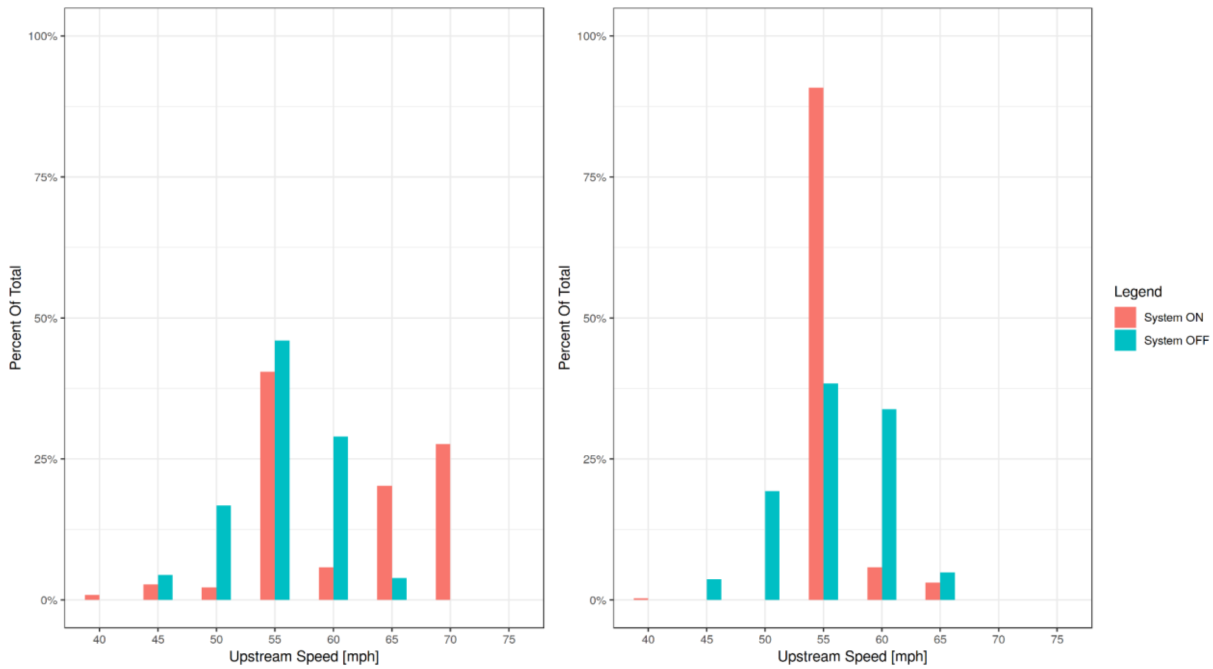


Figure 5.7 Johnson Pkwy Station. Upstream Speed. Reduced Lanes and 4-Lane No-Shoulder

It is interesting to note that the speeds on the upstream detector station didn't change much between the two layouts. Notice, on the days the system was on and there was a capacity reduction some speeds were actually higher. One can hypothesize that under all-lanes open conditions, drivers are approaching the congestion at normal speeds. Given that there is no reduction in lanes, they do not pay attention to the messages on the trailers, but because they are able to use more lanes to decelerate, they generate a smoother slow down similar to the one achieved by the system under reduced capacity conditions.

Figure 5.8 and **Figure** 5.9 present the messages displayed on the three upstream trailers (TH-61, Ruth St, and Hudson Rd) during the estimated time each sampled vehicle passed next to the trailer assuming it entered the freeway on a ramp more than 2 miles upstream of Johnson Pkwy. This is an assumption that cannot be individually tested but over the very large number of samples it is considered a safe one. The labels on the X-Axis read in the direction of traffic so, for example, in **Figure** 5-8, during the Four_Lane_Narrow layout, the highest peak (5^{th} set of bars from the left) indicates that 14% of the drivers that joined the queue in the field of view of the Johnson Pkwy camera, were exposed to no-message (blank) trailers on Hudson and Ruth while the trailer on TH-61 (<2,000 feet upstream) displayed a "40 MPH ½ Mile Ahead" message. From this figure it is clear that misleading messages were displayed very often. Technically speaking, since all the sampled vehicles encountered the queue less than 2,000 feet downstream of the TH-61 trailer, any displayed message other than "Stopped Traffic Ahead" or "15 MPH ½ Mile Ahead" would be inaccurate.

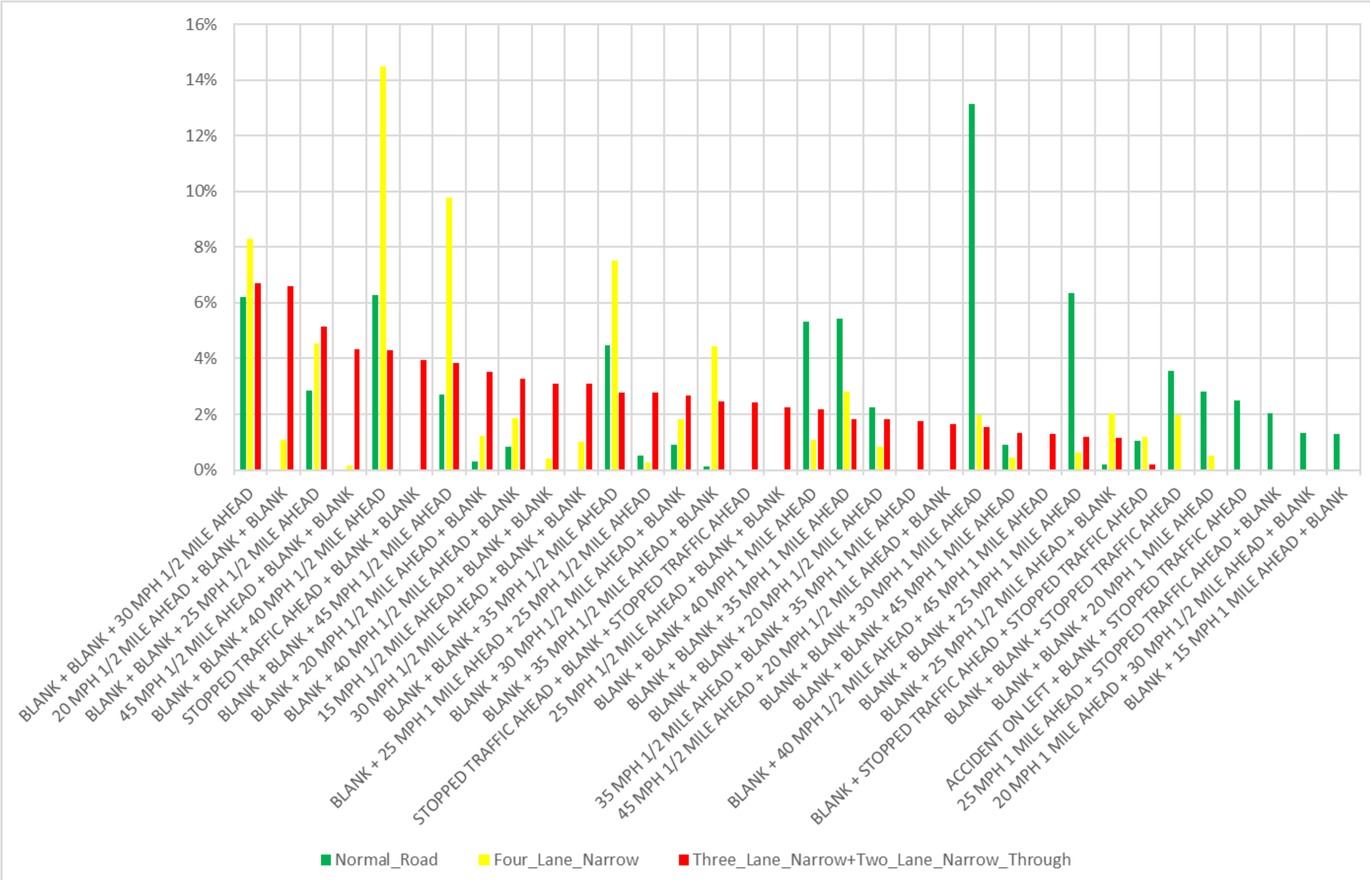


Figure 5.8 Johnson Pkwy Queued Vehicles Message history over last three trailers (three layouts)

The deceleration results presented in this section were combined to form two groups, reduced capacity and full # of lanes road layouts. **Figure** 5.9 presents the messages drivers were exposed to when the Normal_Road and Four_Lanes_Reduced cases are combined. The aforementioned frequent display of inaccurate downstream condition messages is still evident but it is observed that the frequency of such misleading information is less frequent under the restricted capacity periods which agrees with the better performance observed during these periods.

It is very important to emphasize that the SWZSNS, even under such erratic and counterproductive operation, still resulted in the benefits presented in **Figure** 5.4. One can only imagine the impact this system can have if its algorithm and detection infrastructure prompt it to produce more accurate and reliable information.

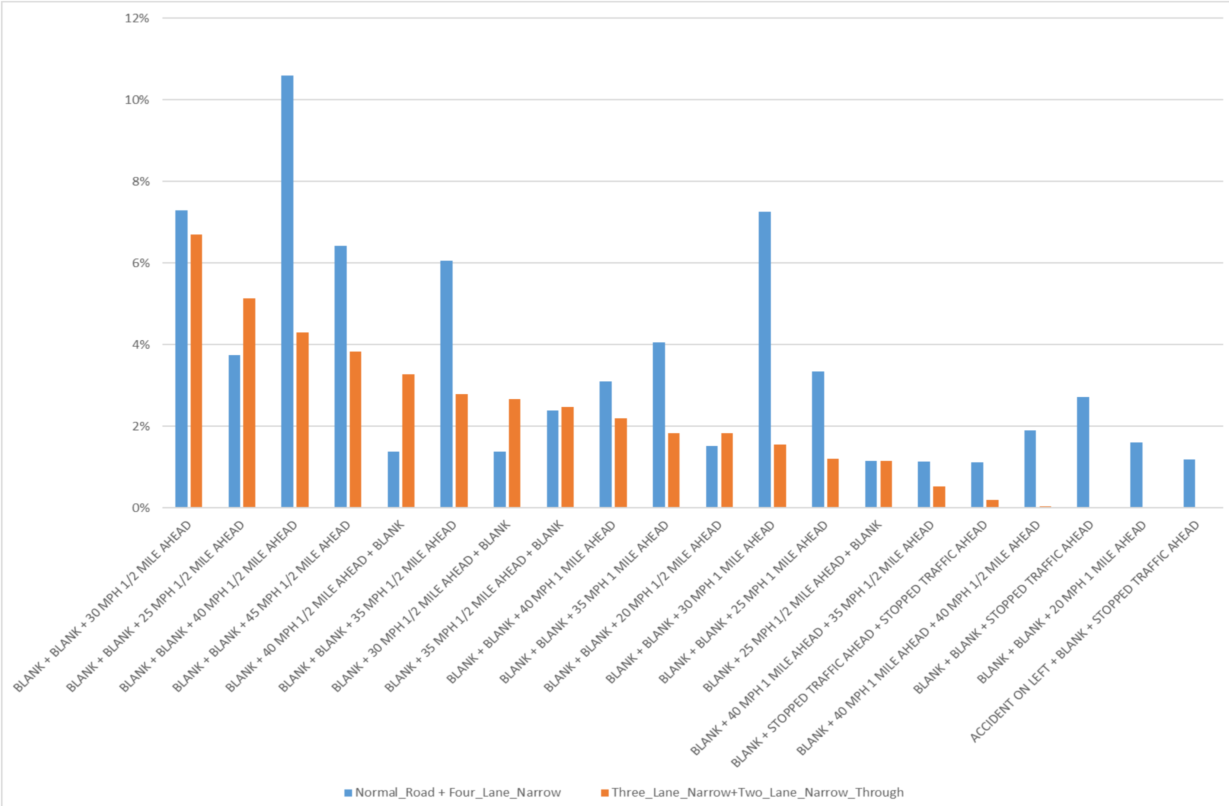


Figure 5.9 Johnson Pkwy Queued Vehicles Message History over last three trailers (combined layouts)

5.1.1 Johnson Pkwy Speed Notification Message Correlation to Deceleration Rates

The following section presents the result of a correlation and causality analysis investigating the relationship between drivers' selected deceleration rates at the back of the queue with the various trailer messages they have experienced upstream of the queue location. This analysis is exploratory and involved a very large number of generalized linear models combining the various driver stimulus (messages) with the measured driver response (selected deceleration). For brevity, only results that support /disprove selected hypothesis are presented.

In the following regression results, the sign of the deceleration was fixed in such a way that negative coefficients result in a reduction of the numerical value and positive indicate an increase in the numerical value of deceleration. The hypothesis is that informed drivers are not surprised when they are encountered by the queue and the need to decelerate to a slow or stop speed.

In the included results, only predictors with bordering or better statistical significance are presented. Red color indicates a detrimental to safety effect while green indicates a beneficial to safety influence of the particular message combinations. Trailer 6 was analyzed separately because it is located right on the position of the queue and it is difficult to differentiate between driver reactions due to the message vs due to the visual view of the queue itself.

5.1.1.1 Work Zone Days with Reduced Lanes

In the following table the combined results of several linear regressions are presented. In the first row of the table the general model followed is presented. A plus (+) sign between predictors represents an independent representation while a star (*) sign indicates that all possible combinations between these predictors were considered. This translates into the combined messages from different trailer and the examination of the effect from the combined sequence of messages as opposed to the individual influence from each message/trailer. The overall average Deceleration is 11ft/sec^2 and the system being in operation immediately reduces that by 8ft/sec^2. The coefficients on the messages are additional adjustments showing the positive or negative influence of each message as compared to the rest.

Table 5-1 Correlation and significance results for Johnson Pkwy during Reduced Lane layouts

acceleration_rate ~ upstream_speed + system_on + v94w06t_message + v94w04t_message + v94w05t_message

Coefficients:

	Estimate	Std. Error	t value	Pr(>|t|)	
(Intercept)	11.27871	0.75071	-6.019	2.12e-09	***
upstream_speed	0.30063	0.01419	21.185	< 2e-16	***
system_on = TRUE	-8.68450	0.13951	-62.248	< 2e-16	***
v94w06t_35 MPH 1/2 MILE AHEAD	1.68837	0.31405	5.376	8.60e-08	***
v94w06t_40 MPH 1/2 MILE AHEAD	2.46693	0.31807	7.756	1.45e-14	***
v94w06t_45 MPH 1/2 MILE AHEAD	2.97931	0.45198	6.592	5.69e-11	***

	Estimate	Std. Error	t value	Pr(>|t|)	
(Intercept)	11.79717	0.74099	-6.474	1.23e-10	***
upstream_speed	0.30593	0.01401	21.841	< 2e-16	***
system_on = TRUE	-8.69510	0.16964	-51.256	< 2e-16	***
v94w04t_30 MPH 1 MILE AHEAD	4.44270	1.52651	2.910	0.003655	**
v94w04t_45 MPH 1 MILE AHEAD	2.82842	0.68691	4.118	4.00e-05	***
v94w04t_45 MPH 1/2 MILE AHEAD	4.41109	1.21885	3.619	0.000304	***
v94w05t_20 MPH 1/2 MILE AHEAD	1.28569	0.54306	2.368	0.018015	*
v94w05t_25 MPH 1 MILE AHEAD	-2.33655	0.68957	-3.388	0.000718	***
v94w05t_30 MPH 1 MILE AHEAD	1.55212	0.60954	2.546	0.010968	*
v94w05t_35 MPH 1 MILE AHEAD	3.68668	0.38493	9.577	< 2e-16	***
v94w05t_35 MPH 1/2 MILE AHEAD	1.57839	0.73986	2.133	0.033031	*
v94w05t_40 MPH 1 MILE AHEAD	2.29765	0.66473	3.457	0.000560	***
v94w05t_45 MPH 1/2 MILE AHEAD	1.28063	0.51291	2.497	0.012623	*

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

From the above analysis, prior observations that some message combinations may have detrimental influence on the driving behavior is again supported. Since, in all cases the queue tail was encountered exactly 1 mile downstream of Trailer 4 and 0.5 miles downstream of Trailer 5, messages that indicated higher than 30mph speeds downstream of these trailers seem to have misinformed the drivers and increased the final deceleration rates (marked with Red Color). In other words, we can hypothesize that the drivers were expecting to encounter the queue later or not at all and their attention was relaxed.

In difference , when the displayed message was correct in terms of the eventual encounter with the queue , the drivers seem to have responded with lower deceleration rates implying that they were more aware and attentive and not surprised by the encountered congestion.

In **Table** 5-2 the combined effect from the sequence of messages encountered as drivers passed next to each of the three trailer DMS is explored. The table rows are sorted so influence ranges from positive to negative in magnitude. Note that it is not possible to guarantee that all the vehicles for which the decelerations were sampled were exposed to all three messages. Given the speeds of the upstream sections, these would be the messages seen by the driver of a hypothetical vehicle that entered the freeway upstream of trailer 4 and captured by the project camera on Johnston performing a deceleration. The data include a few messages that were manually displayed before the system was officially turned on. These messages were introduced in response to incidents that had also caused congestion near the Johnson station.

It is unclear why the two cases where Trailer #5 correctly displayed “Stopped Traffic Ahead” generated negative effects. In both cases, 0.5 miles upstream on Trailer 4 the message was inconsistent and the combination may have generated confusion downplaying the importance of the Trailer 5 message.

Table 5-2 Combined Effect Analysis on Johnson Pkwy for Trailers 4, 5, and 6 during Reduced Lane layouts

Trailer 4	Trailer 5	Trailer 6	Coef	
BLANK	BLANK	WATCH FOR SLOW TRAFFIC	-3.91	**
BLANK	WATCH FOR SLOW TRAFFIC	WATCH FOR SLOW TRAFFIC	-3.42	*
BLANK	25 MPH 1 MILE AHEAD	25 MPH 1/2 MILE AHEAD	-2.75	**
BLANK	25 MPH 1 MILE AHEAD	35 MPH 1/2 MILE AHEAD	-2.35	*
45 MPH 1 MILE AHEAD	40 MPH 1/2 MILE AHEAD	BLANK	-2.23	**
BLANK	40 MPH 1/2 MILE AHEAD	BLANK	1.11	**
25 MPH 1 MILE AHEAD	25 MPH 1/2 MILE AHEAD	BLANK	1.38	*
BLANK	20 MPH 1/2 MILE AHEAD	BLANK	1.42	**
BLANK	BLANK	45 MPH 1/2 MILE AHEAD	1.72	*
BLANK	35 MPH 1/2 MILE AHEAD	BLANK	2.15	*
BLANK	45 MPH 1/2 MILE AHEAD	35 MPH 1/2 MILE AHEAD	2.23	***
BLANK	40 MPH 1 MILE AHEAD	45 MPH 1/2 MILE AHEAD	2.73	***
45 MPH 1 MILE AHEAD	30 MPH 1 MILE AHEAD	40 MPH 1/2 MILE AHEAD	3.50	***
BLANK	BLANK	35 MPH 1/2 MILE AHEAD	3.56	*
45 MPH 1/2 MILE AHEAD	STOPPED TRAFFIC AHEAD	BLANK	3.71	***
BLANK	30 MPH 1 MILE AHEAD	45 MPH 1/2 MILE AHEAD	3.72	**
30 MPH 1 MILE AHEAD	STOPPED TRAFFIC AHEAD	BLANK	3.74	**
45 MPH 1 MILE AHEAD	40 MPH 1/2 MILE AHEAD	45 MPH 1/2 MILE AHEAD	4.80	***
BLANK	35 MPH 1 MILE AHEAD	40 MPH 1/2 MILE AHEAD	5.03	***
BLANK	35 MPH 1 MILE AHEAD	35 MPH 1/2 MILE AHEAD	6.85	***
BLANK	35 MPH 1 MILE AHEAD	45 MPH 1/2 MILE AHEAD	9.10	***
45 MPH 1 MILE AHEAD	40 MPH 1/2 MILE AHEAD	40 MPH 1/2 MILE AHEAD	11.04	***

As can be seen in **Figure** 5.8, for the reduced lane layout days, the most common messages (leftmost columns) involved only messages on Trailer 6. The above table does not contain the first three messages suggesting that although the algorithm frequently utilized Trailer 6, the messages displayed did not result in a statistically significant deceleration rate change by the drivers. The first Most common message that resulted in a significant positive influence on drivers "Blank – 25mph 1 mile – 25mph ½ mile" was used in approximately 3% of the cases.

5.1.1.2 Work Zone Days with Normal Road Conditions

In the following **Table** the similar results are presented for days where the work zone had all lanes open. As shown in the earlier empirical analysis, the system did not add much value in the case of Normal Road mainly because decelerations were considerably lower in general (average 4ft/sec^2). Regardless, the results show that even this way the drivers did notice the signs and their behavior was influenced in both positive and negative ways.

Table 5-3 Correlation and significance results for Johnson Pkwy during Normal Road layout

```
acceleration_rate ~ upstream_speed + system_on + v94w06t_message +
                              v94w04t_message * v94w05t_message

Coefficients:
                                      Estimate Std. Error t value Pr(>|t|)
(Intercept)                            4.24836   0.26181   0.949   0.3429
upstream_speed                         0.08384   0.00474  17.686  < 2e-16 ***
system_on = TRUE                      -0.14582   0.17596  -0.829   0.4073
v94w06t_15 MPH 1/2 MILE AHEAD          4.36653   3.09702   1.410   0.1586
v94w06t_20 MPH 1 MILE AHEAD            6.37120   3.09678   2.057   0.0397 *
v94w06t_20 MPH 1/2 MILE AHEAD          0.96776   0.38523   2.512   0.0120 *
v94w06t_30 MPH 1/2 MILE AHEAD         -0.59074   0.23023  -2.566   0.0103 *
v94w06t_35 MPH 1/2 MILE AHEAD         -0.57570   0.28945  -1.989   0.0468 *
v94w06t_40 MPH 1/2 MILE AHEAD         -1.06180   0.22946  -4.627 3.81e-06 ***

Coefficients:
                                        Estimate   Std. Error   t value Pr(>|t|)
(Intercept)                             4.074545   0.314065   6.605 4.45e-11 ***
upstream_speed                          0.044667   0.006068   7.361 2.18e-13 ***
system_on = TRUE                       -0.319707   0.237076  -1.349 0.177555
v94w04t_45 MPH 1 MILE AHEAD            -1.932070   0.930346  -2.077 0.037887 *
v94w05t_STOPPED TRAFFIC AHEAD           1.034185   0.277685   3.724 0.000198 ***
v94w05t_25 MPH 1 MILE AHEAD             2.155610   0.498073   4.328 1.54e-05 ***
v94w05t_30 MPH 1 MILE AHEAD             3.074882   0.356575   8.623  < 2e-16 ***
v94w05t_35 MPH 1 MILE AHEAD             3.290466   0.296712  11.090  < 2e-16 ***
v94w05t_40 MPH 1 MILE AHEAD             2.695090   0.567270   4.751 2.09e-06 ***
v94w04t_25 MPH 1/2 MILE AHEAD : v94w05t_STOPPED TRAFFIC AHEAD
                                       -3.204019   0.775794  -4.130 3.70e-05 ***
v94w04t_35 MPH 1 MILE AHEAD : v94w05t_STOPPED TRAFFIC AHEAD
                                       -3.579923   1.217110  -2.941 0.003286 **
v94w04t_35 MPH 1/2 MILE AHEAD : v94w05t_STOPPED TRAFFIC AHEAD
                                       -1.778566   0.649424  -2.739 0.006194 **
v94w04t_45 MPH 1/2 MILE AHEAD : v94w05t_STOPPED TRAFFIC AHEAD
                                       -1.611372   0.717749  -2.245 0.024817 *
v94w04t_30 MPH 1 MILE AHEAD : v94w05t_25 MPH 1/2 MILE AHEAD
                                       -3.700578   1.709153  -2.165 0.030431 *
v94w04t_35 MPH 1 MILE AHEAD : v94w05t_25 MPH 1/2 MILE AHEAD
                                       -3.114680   1.251545  -2.489 0.012860 *
v94w04t_40 MPH 1/2 MILE AHEAD : v94w05t_40 MPH 1/2 MILE AHEAD
                                        1.549941   0.617549   2.510 0.012116 *

Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

The analysis had more good measurements secured during Normal Road conditions with and without the system activated. This resulted in a little more resolution in the results, with some message combinations showing statistically significant influence on the drivers' selection of deceleration at the tail of the congestion queue.

Similar to the previous discussion, in the case of Normal Road we see that the speed notification system has an influence on the driver behavior highlighting the suggestion that the system can be useful as a Queue Warning solution under regular traffic operations and not only in the case of an active work zone. Naturally, the overarching suggestion is that the message selection algorithm needs to be improved to reduce if not eliminate the display of detrimental messages.

In the case of Normal Road geometric layout conditions, strong messages like "Stopped Traffic Ahead "on Trailer 5 had a significant positive effect in driver attention as evidenced through the selected deceleration rates. In difference, erroneous messages suggesting the existence of a queue farther downstream than where it really was, or of higher speeds suggesting no congested conditions, support the hypothesis that drivers relaxed their attention on the road and when they encountered the queue they had too implemented higher levels of deceleration.

Table 5-4 Combined Effect Analysis on Johnson Pkwy for Trailers 4, 5, and 6 during Normal Road layouts

Trailer 4	Trailer 5	Trailer 6	Coef	
25 MPH 1/2 MILE AHEAD	STOPPED TRAFFIC AHEAD	STOPPED TRAFFIC AHEAD	-2.20	*
BLANK	25 MPH 1/2 MILE AHEAD	30 MPH 1/2 MILE AHEAD	-2.05	*
45 MPH 1 MILE AHEAD	BLANK	BLANK	-2.00	*
25 MPH 1 MILE AHEAD	35 MPH 1/2 MILE AHEAD	BLANK	-1.91	**
25 MPH 1 MILE AHEAD	25 MPH 1/2 MILE AHEAD	BLANK	-1.73	*
35 MPH 1 MILE AHEAD	25 MPH 1/2 MILE AHEAD	BLANK	-1.63	*
45 MPH 1/2 MILE AHEAD	40 MPH 1/2 MILE AHEAD	BLANK	-1.48	*
40 MPH 1 MILE AHEAD	40 MPH 1/2 MILE AHEAD	40 MPH 1/2 MILE AHEAD	-0.89	*
BLANK	STOPPED TRAFFIC AHEAD	STOPPED TRAFFIC AHEAD	0.96	**
BLANK	45 MPH 1/2 MILE AHEAD	45 MPH 1/2 MILE AHEAD	1.12	.
35 MPH 1/2 MILE AHEAD	BLANK	STOPPED TRAFFIC AHEAD	1.15	**
BLANK	40 MPH 1/2 MILE AHEAD	45 MPH 1/2 MILE AHEAD	1.24	.
BLANK	45 MPH 1/2 MILE AHEAD	BLANK	1.38	***
BLANK	40 MPH 1/2 MILE AHEAD	BLANK	1.42	*
35 MPH 1 MILE AHEAD	BLANK	BLANK	1.61	.
BLANK	35 MPH 1 MILE AHEAD	STOPPED TRAFFIC AHEAD	1.81	***
30 MPH 1 MILE AHEAD	30 MPH 1/2 MILE AHEAD	BLANK	2.03	**
40 MPH 1/2 MILE AHEAD	40 MPH 1/2 MILE AHEAD	BLANK	2.08	***
BLANK	25 MPH 1 MILE AHEAD	BLANK	2.08	***
BLANK	30 MPH 1 MILE AHEAD	STOPPED TRAFFIC AHEAD	2.82	***
30 MPH 1/2 MILE AHEAD	BLANK	STOPPED TRAFFIC AHEAD	3.76	*
BLANK	STOPPED TRAFFIC AHEAD	20 MPH 1/2 MILE AHEAD	3.92	***
BLANK	35 MPH 1 MILE AHEAD	BLANK	4.49	***
45 MPH 1/2 MILE AHEAD	40 MPH 1/2 MILE AHEAD	30 MPH 1/2 MILE AHEAD	4.88	.
BLANK	40 MPH 1 MILE AHEAD	BLANK	4.98	***
BLANK	30 MPH 1 MILE AHEAD	BLANK	5.79	***
45 MPH 1 MILE AHEAD	45 MPH 1/2 MILE AHEAD	20 MPH 1 MILE AHEAD	7.08	*

In general, from all the evidence, the hypothesis that the Speed Notification System has a noticeable influence on driver attention levels is supported. Also, the results suggest that when the system provides accurate messages to the drivers the effect is positive in regards to safety but when the messages are misleading the system can make things worse.

5.2 TH-61 STATION TRAJECTORY ANALYSIS

Figure 5.10 TH-61 Station. All Lanes Open. Normal Road, 3-lane No Shoulder

Figure 5.11 TH-61 Station. Reduced Lanes Layouts. 2-Lane No Shoulder, 2-Lane No Shoulder Through only

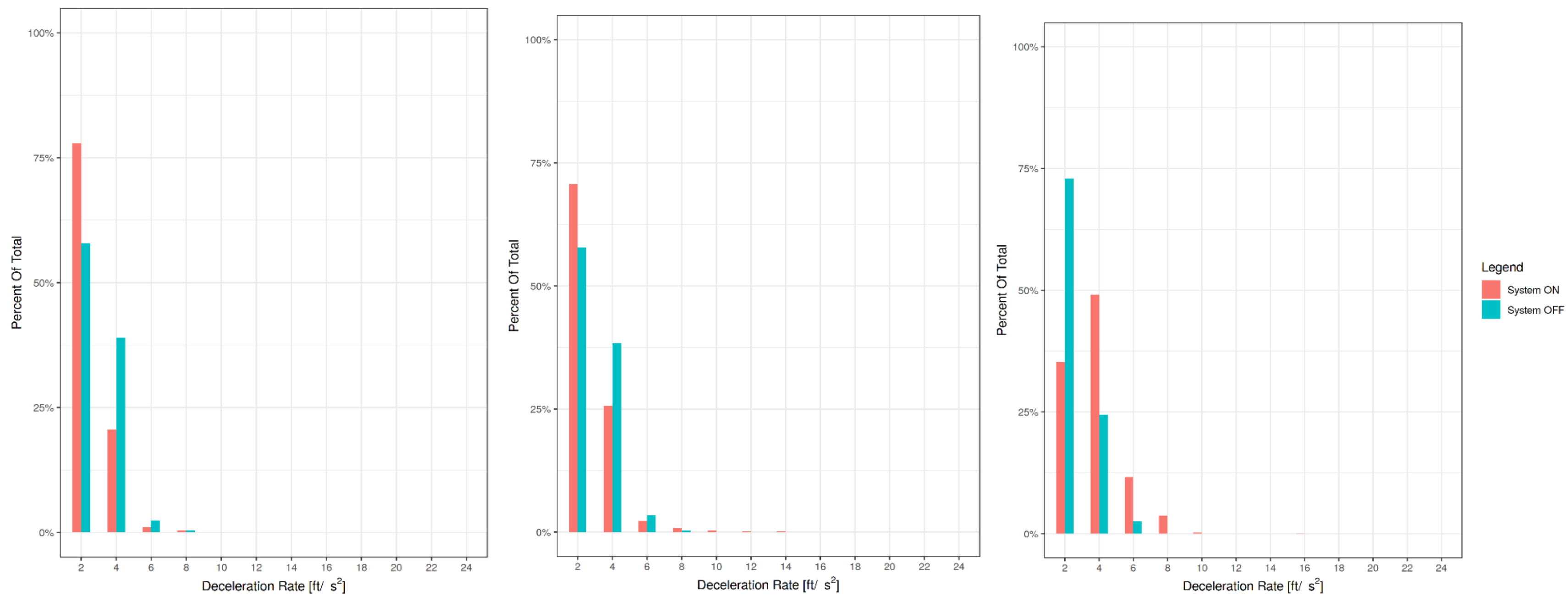


Figure 5.12 TH-61 Station. Calculated Deceleration. 3-Lane No Shoulder, Normal Road, Reduced Lanes Layouts

The project observed the conditions of the queue buildup on the TH-61 station during three layouts that used both with and without the system. On **Figure** 5.12, calculated decelerations are presented for two cases where there were no reduction in number of lanes (leftmost is all lanes open but no shoulder and middle is normal road conditions). In this location, although the system did not cause substantial difference as compared to the case of Johnson Ave, it seems that it helped reduce decelerations when the road is with all lanes open while there were no benefit on the days with reduced capacity.

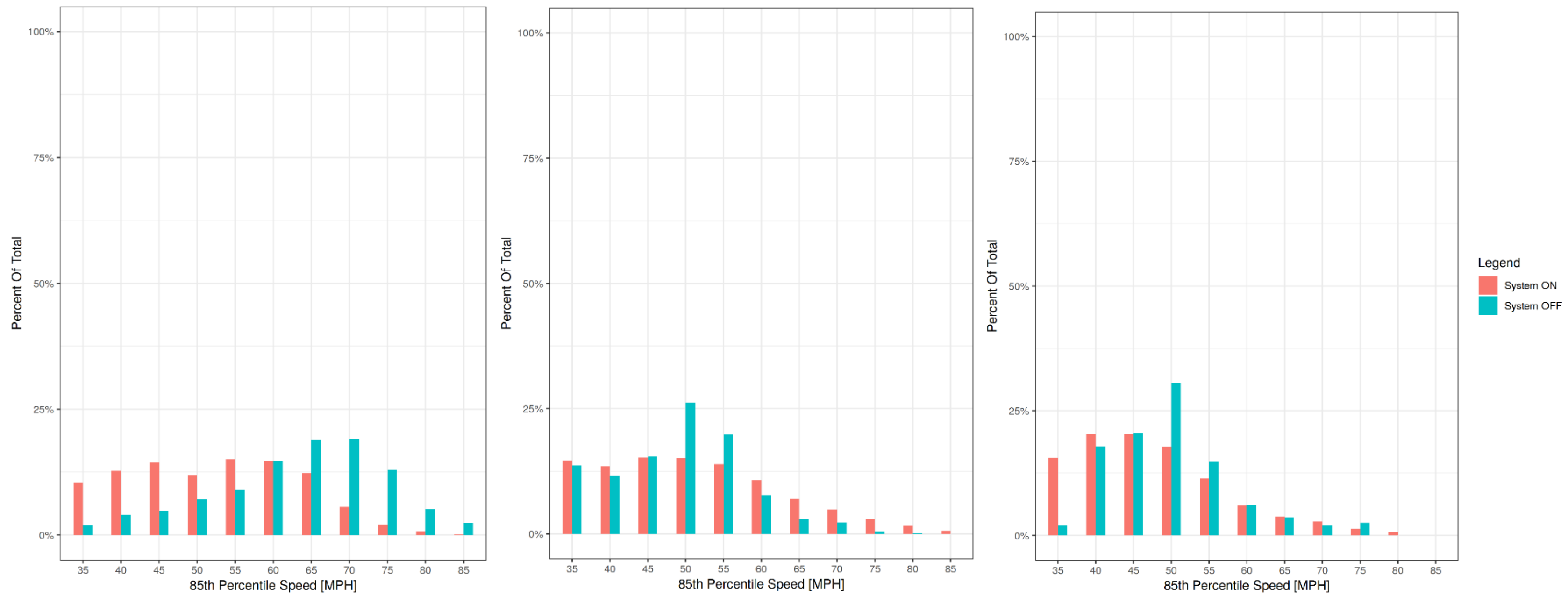


Figure 5.13 TH-61 Station. 85th-Percentile Speed. 3-Lane No Shoulder, Normal Road, Reduced Lanes Layouts

An explanation for this phenomenon can be found on the 85th-percentile speeds of vehicles as they approach the back of the queue. In **Figure** 5.13 we observe that the approach speeds under all-lanes open are much higher without the system while with the system they are more uniform and slightly lower. Under the reduced capacity conditions these speeds are already low in either cases which can be explained by having much more rapid spread of the congestion and the system did not have time to react. Note that the speed notification trailer is only 1000 feet upstream of the data collection station and it is influenced primarily by the conditions on Johnson Ave.

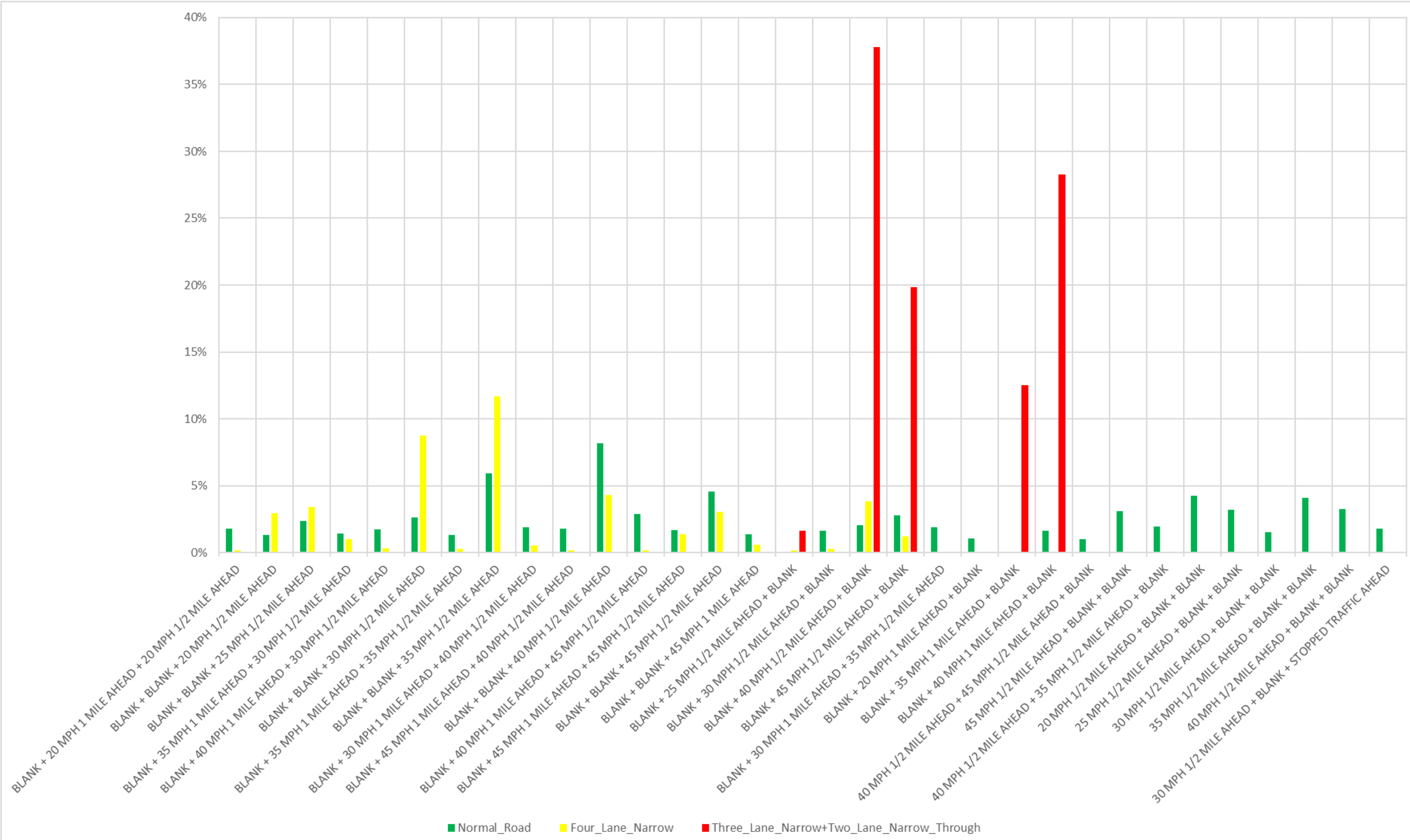


Figure 5.14 TH-61 Queued Vehicles Message history over last three trailers (three layouts)

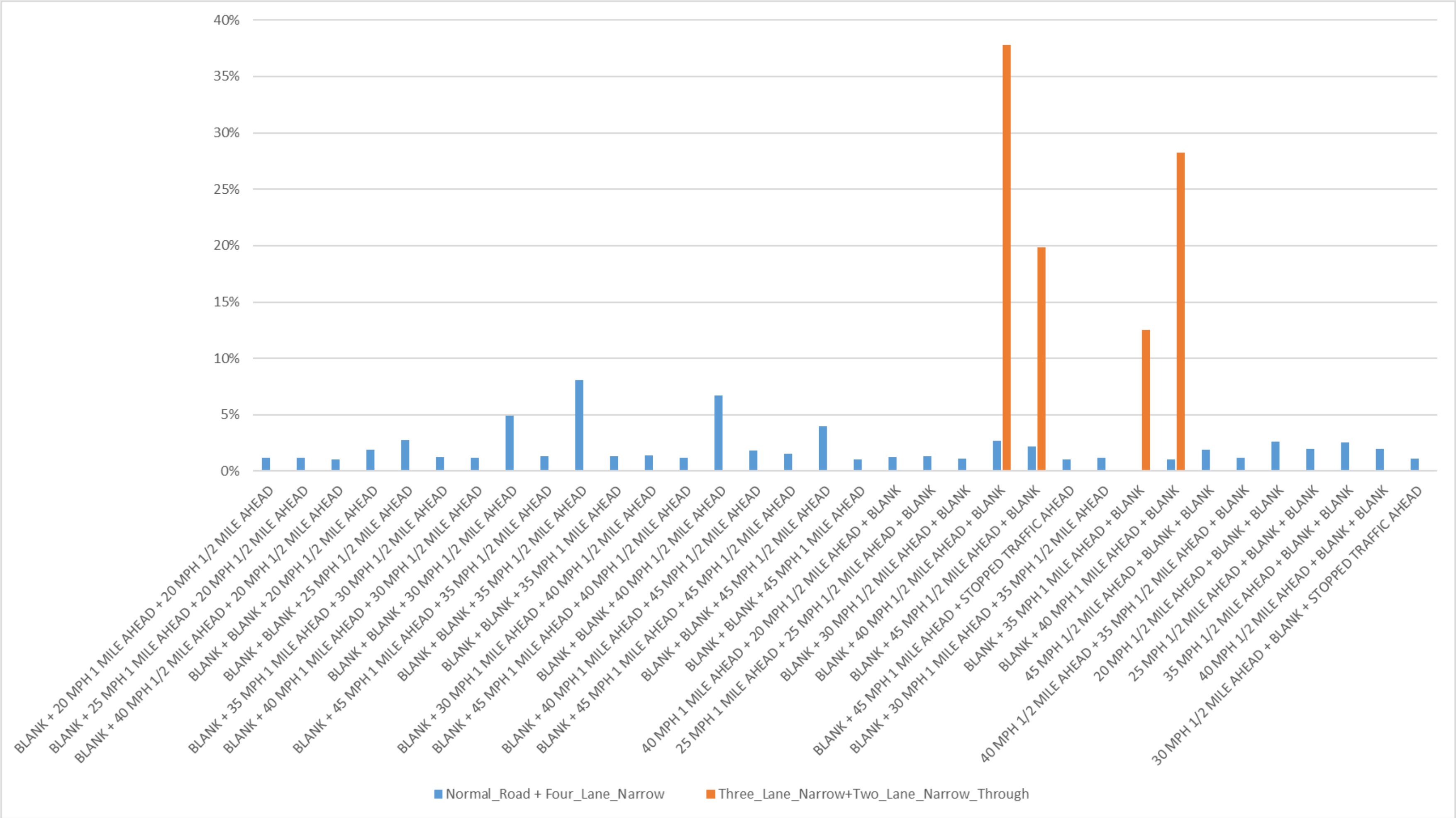


Figure 5.15 TH-61 Queued Vehicles Message history over last three trailers (combined layouts)

5.2.1 TH-61 Trailer Message Correlation to Deceleration Rates

The following section presents the result of a correlation and causality analysis investigating the relationship between the messages displayed on the trailers upstream of the TH-61 queue and the selected driver deceleration. Similarly to the previous sections, the results are presented for individual Trailer message influence as well in regards to the combination of the three upstream messages encountered. Negative coefficient (Green) suggest a reduction in implemented deceleration, a positive outcome, while a positive coefficient (Red) suggests an increase in deceleration, a negative outcome.

5.2.1.1 Work Zone Days with Reduced Lanes

Table 5-5 Correlation and significance results for TH-61 during Reduced Lane layouts

acceleration_rate ~ upstream_speed + system_on + v94w05t_message + v94w04t_message + v94w03t_message

Coefficients:

	Estimate	Std. Error	t value	Pr(>|t|)	
(Intercept)	-3.844470	0.560558	-6.858	7.79e-12	***
upstream_speed	0.171721	0.006556	26.194	< 2e-16	***
system_on = TRUE	-4.078799	1.605686	-2.540	0.011107	*
v94w05t_20 MPH 1/2 MILE AHEAD	1.119574	0.448463	2.496	0.012575	*
v94w05t_25 MPH 1/2 MILE AHEAD	1.572395	0.317085	4.959	7.32e-07	***
v94w05t_30 MPH 1/2 MILE AHEAD	2.105218	0.312864	6.729	1.90e-11	***
v94w05t_35 MPH 1/2 MILE AHEAD	0.893119	0.279688	3.193	0.001415	**
v94w05t_40 MPH 1 MILE AHEAD	4.068057	0.466020	8.729	< 2e-16	***
v94w05t_45 MPH 1 MILE AHEAD	1.826055	0.504830	3.617	0.000301	***
v94w05t_45 MPH 1/2 MILE AHEAD	1.354290	0.282528	4.793	1.69e-06	***
v94w04t_STOPPED TRAFFIC AHEAD	-3.119433	1.381466	-2.258	0.023984	*
v94w04t_20 MPH 1/2 MILE AHEAD	-2.836968	0.580810	-4.885	1.07e-06	***
v94w04t_25 MPH 1/2 MILE AHEAD	1.564469	0.369993	4.228	2.39e-05	***
v94w04t_30 MPH 1/2 MILE AHEAD	-0.684087	0.323710	-2.113	0.034626	*
v94w04t_40 MPH 1 MILE AHEAD	-3.729673	1.382294	-2.698	0.006995	**
v94w04t_45 MPH 1 MILE AHEAD	-2.032199	0.910963	-2.231	0.025736	*
v94w04t_45 MPH 1/2 MILE AHEAD	1.073046	0.333446	3.218	0.001299	**
v94w03t_20 MPH 1/2 MILE AHEAD	6.752774	1.610236	4.194	2.79e-05	***
v94w03t_25 MPH 1/2 MILE AHEAD	6.595892	1.632654	4.040	5.42e-05	***
v94w03t_40 MPH 1/2 MILE AHEAD	7.631203	3.181633	2.399	0.016497	*
v94w03t_BLANK	5.738313	1.545282	3.713	0.000207	***

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Although there is a small positive overall influence from the speed notification system on the TH-61 queue encounters, a lot of messages on the last trailer (Trailer 5) display a negative influence. One possible explanation for this observation is that Trailer 5 was at most 1000 feet upstream of the location where the queue was observed and the deceleration measured. This translates to having any other message except "Stopped Traffic Ahead" being misleading. I difference, when messages on Trailer 4 (0.7 miles upstream of the queue) were reasonable they had a positive influence on driver behavior.

Table 5-6 presents the results for the combined effect of trailers 3, 4, and 5. In this case, reasonable messages on both Trailers 4 and 5 generated a beneficial outcome although an unreasonable message on Trailer 4 seems to override much of the influence of Trailer 5. Trailer 3 seems to be in general not having much of influence in this section.

Table 5-6 Combined Effect Analysis on TH-61 for Trailers 3, 4, and 5 during Reduced Lane layouts

Trailer 3	Trailer 4	Trailer 5	Coeff.	
40 MPH 1/2 MILE AHEAD	15 MPH 1/2 MILE AHEAD	STOPPED TRAFFIC AHEAD	-6.41697	***
15 MPH 1/2 MILE AHEAD	BLANK	BLANK	-5.87043	.
STOPPED TRAFFIC AHEAD	BLANK	BLANK	-5.73546	***
BLANK	25 MPH 1 MILE AHEAD	40 MPH 1/2 MILE AHEAD	-5.27823	*
BLANK	45 MPH 1/2 MILE AHEAD	40 MPH 1/2 MILE AHEAD	-4.38511	*
BLANK	25 MPH 1 MILE AHEAD	30 MPH 1/2 MILE AHEAD	-4.2401	.
BLANK	30 MPH 1 MILE AHEAD	30 MPH 1/2 MILE AHEAD	-4.20146	***
45 MPH 1/2 MILE AHEAD	BLANK	40 MPH 1/2 MILE AHEAD	-3.78413	.
BLANK	40 MPH 1 MILE AHEAD	BLANK	-3.72855	**
BLANK	STOPPED TRAFFIC AHEAD	BLANK	-3.11984	*
BLANK	30 MPH 1 MILE AHEAD	40 MPH 1/2 MILE AHEAD	-2.9683	**
BLANK	20 MPH 1/2 MILE AHEAD	BLANK	-2.83657	***
BLANK	40 MPH 1/2 MILE AHEAD	20 MPH 1/2 MILE AHEAD	-2.75164	***
BLANK	30 MPH 1 MILE AHEAD	45 MPH 1/2 MILE AHEAD	-2.70827	**
BLANK	40 MPH 1 MILE AHEAD	30 MPH 1/2 MILE AHEAD	-2.55505	*
BLANK	30 MPH 1 MILE AHEAD	35 MPH 1/2 MILE AHEAD	-2.42248	**
BLANK	30 MPH 1/2 MILE AHEAD	30 MPH 1/2 MILE AHEAD	-2.31046	**
BLANK	40 MPH 1 MILE AHEAD	25 MPH 1/2 MILE AHEAD	-2.25048	***
BLANK	40 MPH 1/2 MILE AHEAD	30 MPH 1/2 MILE AHEAD	-2.03401	**
BLANK	45 MPH 1 MILE AHEAD	BLANK	-2.03315	*
BLANK	40 MPH 1 MILE AHEAD	STOPPED TRAFFIC AHEAD	-1.49106	*
BLANK	40 MPH 1/2 MILE AHEAD	35 MPH 1/2 MILE AHEAD	-1.26335	*
BLANK	25 MPH 1/2 MILE AHEAD	STOPPED TRAFFIC AHEAD	-1.0927	*
BLANK	40 MPH 1/2 MILE AHEAD	STOPPED TRAFFIC AHEAD	-0.98423	*
BLANK	30 MPH 1/2 MILE AHEAD	BLANK	-0.68482	*
BLANK	BLANK	40 MPH 1/2 MILE AHEAD	0.46206	.
BLANK	BLANK	STOPPED TRAFFIC AHEAD	0.765217	*
BLANK	BLANK	35 MPH 1/2 MILE AHEAD	0.893605	**
BLANK	45 MPH 1 MILE AHEAD	45 MPH 1/2 MILE AHEAD	0.92028	*
BLANK	45 MPH 1 MILE AHEAD	40 MPH 1/2 MILE AHEAD	0.986553	*
20 MPH 1/2 MILE AHEAD	BLANK	BLANK	1.012873	.
BLANK	45 MPH 1/2 MILE AHEAD	BLANK	1.072385	**
BLANK	BLANK	20 MPH 1/2 MILE AHEAD	1.119618	*
BLANK	35 MPH 1 MILE AHEAD	45 MPH 1/2 MILE AHEAD	1.281838	**
BLANK	BLANK	45 MPH 1/2 MILE AHEAD	1.354785	***
BLANK	25 MPH 1/2 MILE AHEAD	BLANK	1.563491	***
BLANK	BLANK	25 MPH 1/2 MILE AHEAD	1.573162	***
BLANK	45 MPH 1 MILE AHEAD	35 MPH 1/2 MILE AHEAD	1.589046	***
BLANK	BLANK	45 MPH 1 MILE AHEAD	1.82769	***
BLANK	45 MPH 1 MILE AHEAD	25 MPH 1/2 MILE AHEAD	1.96228	***
BLANK	BLANK	30 MPH 1/2 MILE AHEAD	2.106167	***
BLANK	BLANK	35 MPH 1 MILE AHEAD	2.206443	.
BLANK	25 MPH 1/2 MILE AHEAD	20 MPH 1/2 MILE AHEAD	2.434537	**
BLANK	35 MPH 1 MILE AHEAD	30 MPH 1/2 MILE AHEAD	2.670426	**
BLANK	45 MPH 1 MILE AHEAD	20 MPH 1/2 MILE AHEAD	3.019691	***
BLANK	45 MPH 1 MILE AHEAD	30 MPH 1/2 MILE AHEAD	4.048502	***
BLANK	BLANK	40 MPH 1 MILE AHEAD	4.069412	***
BLANK	25 MPH 1 MILE AHEAD	20 MPH 1/2 MILE AHEAD	5.858041	**

In general, as stated earlier, the Speed Notification System was less effective on TH-61 and since a variety of messages were displayed, although their comparative influence shows strong collations with selected decelerations, the patterns are not so informative. Specifically in the case of Reduced Lane layouts, as shown in **Figure** 5.15, only four message combinations were most prevalent while all others represented each less than 1% of the overall combinations. This wide spread generates these plethora of statistically significant correlations with little overall clear pattern on influence on driver behavior. Still, the second most common message combination "BLANK – 45 MPH 1 MILE – BLANK" showed a high correlation to a significant reduction of deceleration rates.

5.2.1.2 Work Zone Days with Normal Road Conditions

Table 5-7 Correlation and significance results for TH-61 during Normal Road layouts

acceleration_rate ~ upstream_speed + system_on + v94w05t_message + v94w04t_message + v94w03t_message					
Coefficients:					
	Estimate	Std. Error	t value	Pr(>|t|)	
(Intercept)	0.09873	0.63452	0.156	0.876378	
upstream_speed	0.07672	0.01280	5.995	2.79e-09	***
system_on = TRUE	1.02435	1.18113	0.867	0.385998	
v94w05t_30 MPH 1/2 MILE AHEAD	-3.90178	0.57592	-6.775	2.08e-11	***
v94w05t_35 MPH 1/2 MILE AHEAD	-1.83107	0.50975	-3.592	0.000343	***
v94w04t_STOPPED TRAFFIC AHEAD	-2.69473	0.66320	-4.063	5.20e-05	***
v94w04t_25 MPH 1 MILE AHEAD	-3.54467	2.06697	-1.715	0.086658	.
v94w04t_15 MPH 1/2 MILE AHEAD	-2.32902	0.86179	-2.703	0.006993	**
v94w04t_20 MPH 1/2 MILE AHEAD	-2.63845	0.54943	-4.802	1.80e-06	***
v94w04t_25 MPH 1/2 MILE AHEAD	-2.55136	0.65187	-3.914	9.67e-05	***
v94w04t_30 MPH 1/2 MILE AHEAD	-2.14385	0.64067	-3.346	0.000848	***
v94w04t_35 MPH 1/2 MILE AHEAD	-2.86972	0.53384	-5.376	9.41e-08	***
v94w04t_40 MPH 1/2 MILE AHEAD	-3.28402	0.53868	-6.096	1.52e-09	***
v94w04t_45 MPH 1/2 MILE AHEAD	-2.98423	0.65756	-4.538	6.33e-06	***

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1					

The above **Table** suggests that although the benefit from the Speed Notification system was marginal during Normal Road layouts (all four lanes open), messages displayed on Trailer 4 had a significant correlation with reductions in deceleration rates at the back of the queue on TH-61 station. Only two messages from Trailer 5 resulted in such benefit possibly because Trailer 5 was only 1000 feet upstream of the queue location and by the time drivers were exposed to Trailer 5 they could potentially also see the queue forming downstream.

Table 5-8 generally suggests that a large number of messages resulted in beneficial correlations to reductions in deceleration rates. Note that the combinations that resulted in the highest reductions in deceleration rates were the ones that had reasonable messages on Trailer 5 or no message (Blank). Towards the bottom of the table where message combinations show the least benefit, Messages on Trailer 5 show unreasonable information suggesting speeds of 40mph and higher or more importantly speeds higher than the ones mentioned in Trailer 4. This finding again reinforces the need for messages to be consistent and coordinated.

Table 5-8 Combined Effect Analysis on TH-61 for Trailers 3, 4, and 5 during Normal Road Layouts

Trailer 3	Trailer 4	Trailer 5	Coeff.	
BLANK	45 MPH 1/2 MILE AHEAD	25 MPH 1/2 MILE AHEAD	-5.47692	***
BLANK	20 MPH 1 MILE AHEAD	15 MPH 1/2 MILE AHEAD	-5.35359	**
BLANK	25 MPH 1/2 MILE AHEAD	BLANK	-4.99159	*
20 MPH 1 MILE AHEAD	15 MPH 1/2 MILE AHEAD	STOPPED TRAFFIC AHEAD	-4.83636	**
35 MPH 1 MILE AHEAD	30 MPH 1/2 MILE AHEAD	30 MPH 1/2 MILE AHEAD	-4.78758	**
20 MPH 1 MILE AHEAD	STOPPED TRAFFIC AHEAD	STOPPED TRAFFIC AHEAD	-4.76155	***
35 MPH 1 MILE AHEAD	30 MPH 1/2 MILE AHEAD	20 MPH 1/2 MILE AHEAD	-4.72009	***
35 MPH 1 MILE AHEAD	45 MPH 1/2 MILE AHEAD	BLANK	-4.57796	*
BLANK	35 MPH 1 MILE AHEAD	25 MPH 1/2 MILE AHEAD	-4.57	*
15 MPH 1 MILE AHEAD	20 MPH 1/2 MILE AHEAD	STOPPED TRAFFIC AHEAD	-4.52219	***
STOPPED TRAFFIC AHEAD	25 MPH 1/2 MILE AHEAD	BLANK	-4.52114	*
40 MPH 1 MILE AHEAD	35 MPH 1/2 MILE AHEAD	STOPPED TRAFFIC AHEAD	-4.29754	***
20 MPH 1 MILE AHEAD	45 MPH 1/2 MILE AHEAD	BLANK	-4.25243	***
45 MPH 1 MILE AHEAD	40 MPH 1/2 MILE AHEAD	BLANK	-4.20467	***
BLANK	35 MPH 1 MILE AHEAD	STOPPED TRAFFIC AHEAD	-4.19979	***
BLANK	STOPPED TRAFFIC AHEAD	BLANK	-4.17756	*
40 MPH 1 MILE AHEAD	40 MPH 1/2 MILE AHEAD	BLANK	-4.09284	***
BLANK	BLANK	30 MPH 1/2 MILE AHEAD	-4.06706	***
30 MPH 1 MILE AHEAD	45 MPH 1/2 MILE AHEAD	BLANK	-4.06222	***
30 MPH 1 MILE AHEAD	25 MPH 1/2 MILE AHEAD	BLANK	-4.01763	***
30 MPH 1 MILE AHEAD	30 MPH 1 MILE AHEAD	20 MPH 1/2 MILE AHEAD	-4.00796	***
35 MPH 1 MILE AHEAD	30 MPH 1/2 MILE AHEAD	BLANK	-3.90628	***
STOPPED TRAFFIC AHEAD	STOPPED TRAFFIC AHEAD	BLANK	-3.88688	**
ACCIDENT ON LEFT	20 MPH 1 MILE AHEAD	STOPPED TRAFFIC AHEAD	-3.81655	*
BLANK	25 MPH 1 MILE AHEAD	25 MPH 1/2 MILE AHEAD	-3.79152	***
BLANK	45 MPH 1 MILE AHEAD	STOPPED TRAFFIC AHEAD	-3.76698	***
BLANK	35 MPH 1/2 MILE AHEAD	20 MPH 1/2 MILE AHEAD	-3.67236	***
25 MPH 1 MILE AHEAD	30 MPH 1/2 MILE AHEAD	BLANK	-3.63046	*
40 MPH 1 MILE AHEAD	20 MPH 1/2 MILE AHEAD	BLANK	-3.6064	***
25 MPH 1 MILE AHEAD	25 MPH 1/2 MILE AHEAD	BLANK	-3.56448	***
45 MPH 1 MILE AHEAD	35 MPH 1/2 MILE AHEAD	STOPPED TRAFFIC AHEAD	-3.56114	*
BLANK	40 MPH 1 MILE AHEAD	35 MPH 1/2 MILE AHEAD	-3.55111	*
BLANK	35 MPH 1 MILE AHEAD	40 MPH 1/2 MILE AHEAD	-3.52292	*
30 MPH 1 MILE AHEAD	45 MPH 1/2 MILE AHEAD	STOPPED TRAFFIC AHEAD	-3.5166	*
25 MPH 1 MILE AHEAD	20 MPH 1/2 MILE AHEAD	BLANK	-3.47478	***
35 MPH 1 MILE AHEAD	35 MPH 1/2 MILE AHEAD	BLANK	-3.45888	***
40 MPH 1 MILE AHEAD	STOPPED TRAFFIC AHEAD	BLANK	-3.41709	***
35 MPH 1 MILE AHEAD	30 MPH 1 MILE AHEAD	STOPPED TRAFFIC AHEAD	-3.39712	*
35 MPH 1 MILE AHEAD	20 MPH 1/2 MILE AHEAD	BLANK	-3.34207	***
45 MPH 1 MILE AHEAD	20 MPH 1/2 MILE AHEAD	BLANK	-3.33251	***
BLANK	40 MPH 1/2 MILE AHEAD	BLANK	-3.28365	***
BLANK	40 MPH 1 MILE AHEAD	STOPPED TRAFFIC AHEAD	-3.25099	***
20 MPH 1 MILE AHEAD	40 MPH 1/2 MILE AHEAD	BLANK	-3.24119	***
BLANK	20 MPH 1 MILE AHEAD	25 MPH 1/2 MILE AHEAD	-3.21111	***
BLANK	25 MPH 1 MILE AHEAD	20 MPH 1/2 MILE AHEAD	-3.1859	***
BLANK	40 MPH 1/2 MILE AHEAD	20 MPH 1/2 MILE AHEAD	-3.12422	***
BLANK	45 MPH 1/2 MILE AHEAD	BLANK	-3.12275	**
BLANK	30 MPH 1 MILE AHEAD	STOPPED TRAFFIC AHEAD	-3.08825	***
20 MPH 1 MILE AHEAD	35 MPH 1/2 MILE AHEAD	BLANK	-3.08346	***
BLANK	35 MPH 1/2 MILE AHEAD	BLANK	-3.0654	***
25 MPH 1 MILE AHEAD	45 MPH 1/2 MILE AHEAD	BLANK	-3.05914	***
30 MPH 1 MILE AHEAD	35 MPH 1/2 MILE AHEAD	20 MPH 1/2 MILE AHEAD	-2.92963	**
BLANK	45 MPH 1 MILE AHEAD	35 MPH 1/2 MILE AHEAD	-2.91557	**
ACCIDENT ON LEFT	STOPPED TRAFFIC AHEAD	STOPPED TRAFFIC AHEAD	-2.87272	**
20 MPH 1 MILE AHEAD	15 MPH 1/2 MILE AHEAD	BLANK	-2.86653	**
BLANK	20 MPH 1 MILE AHEAD	45 MPH 1/2 MILE AHEAD	-2.86425	**
45 MPH 1 MILE AHEAD	STOPPED TRAFFIC AHEAD	BLANK	-2.7499	***
BLANK	35 MPH 1 MILE AHEAD	45 MPH 1/2 MILE AHEAD	-2.71447	***
BLANK	35 MPH 1 MILE AHEAD	35 MPH 1/2 MILE AHEAD	-2.70276	**
40 MPH 1 MILE AHEAD	15 MPH 1/2 MILE AHEAD	BLANK	-2.62717	**
BLANK	25 MPH 1 MILE AHEAD	35 MPH 1/2 MILE AHEAD	-2.61896	*
BLANK	25 MPH 1 MILE AHEAD	45 MPH 1/2 MILE AHEAD	-2.55528	***
BLANK	35 MPH 1 MILE AHEAD	30 MPH 1/2 MILE AHEAD	-2.51942	**
BLANK	30 MPH 1 MILE AHEAD	40 MPH 1/2 MILE AHEAD	-2.42763	**
20 MPH 1 MILE AHEAD	30 MPH 1/2 MILE AHEAD	BLANK	-2.13452	**
BLANK	BLANK	35 MPH 1/2 MILE AHEAD	-2.0096	***
upstream_speeD			0.09094	***
system_onTRUE			2.43836	***

5.3 WHITE BEAR STATION TRAJECTORY ANALYSIS

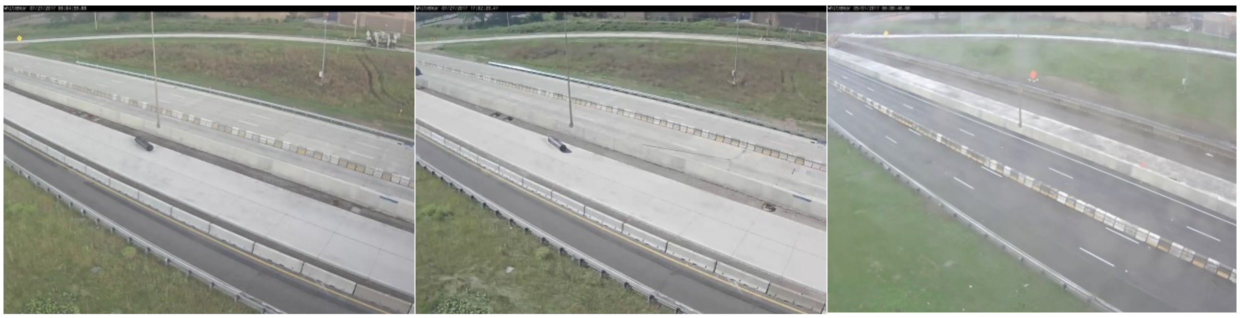


Figure 5.16 White Bear Ave Station. Reduced Lanes Layouts. 3-Lane, 2-Lane, 2-Lane Through only

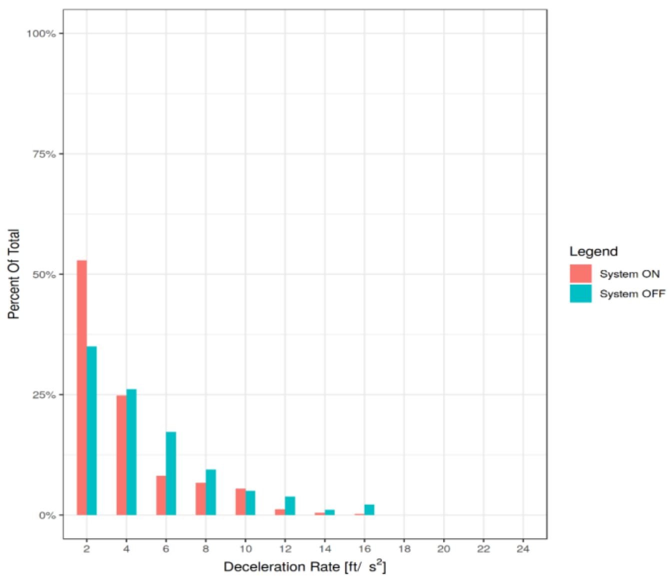


Figure 5.17 White Bear Ave Station. Calculated Deceleration. Reduced Lanes Layouts

On the station at White Bear Ave, as seen in **Figure** 5.17, we observe a noticeable improvement of conditions when the system was online. The trailer displaying the downstream speeds was located a fair distance upstream of the station and as was presented in the 2017 queue frequency graph, less than 50% of the time the queue reached that far and it did it in a much slower pace. The algorithm had enough time to realize the speed drop and warn the drivers a fair distance away from the back of the queue. During all lanes open, the congestion rarely reached that far so no data are available.

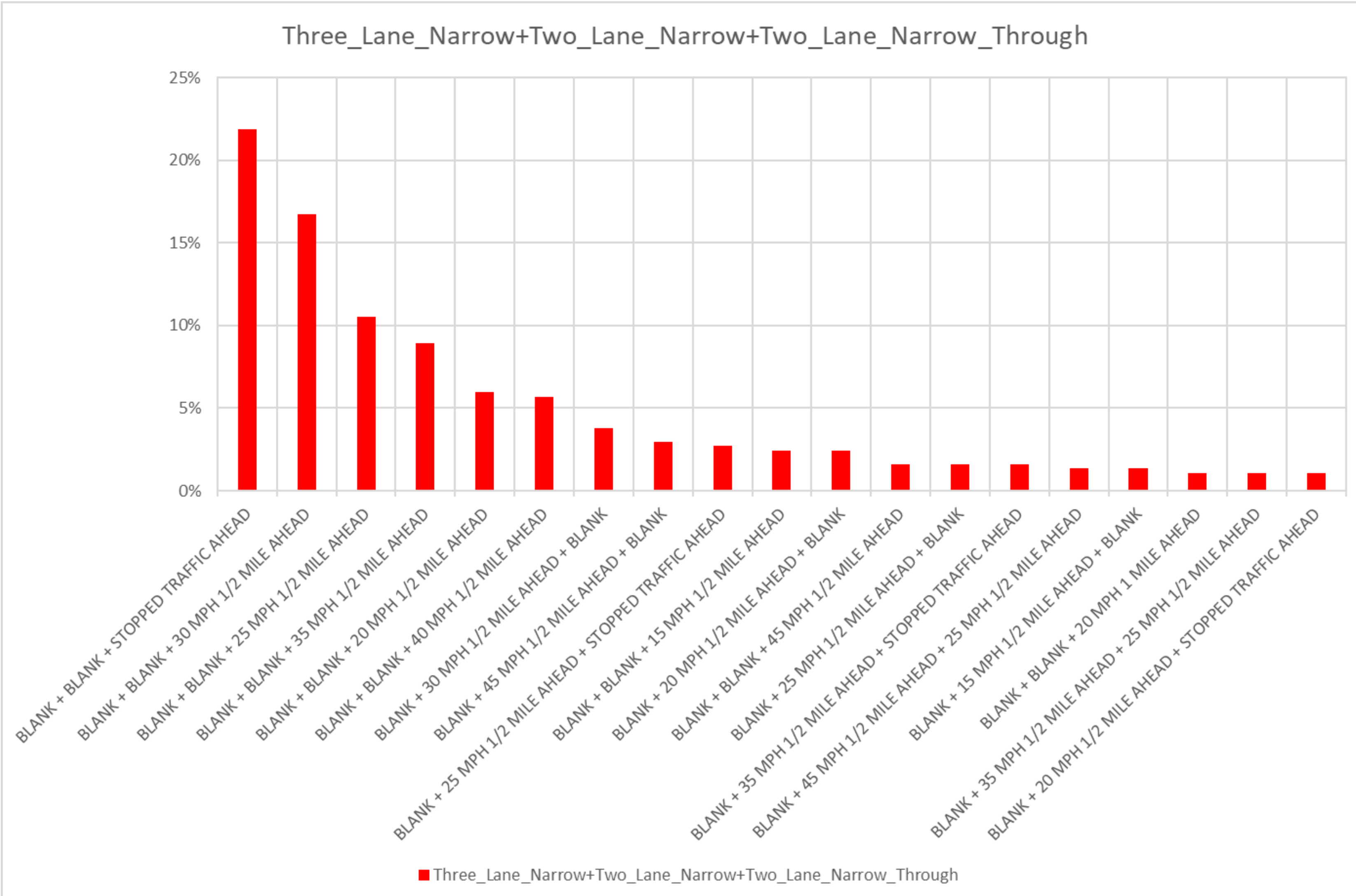


Figure 5.18 White Bear Ave Queued Vehicles Message history over last three trailers

5.4 MCKNIGHT STATION TRAJECTORY ANALYSIS

Figure 5.19 McKnight Ave Station. Reduced Lanes Layouts. 2-Lane, 2-Lane Through only

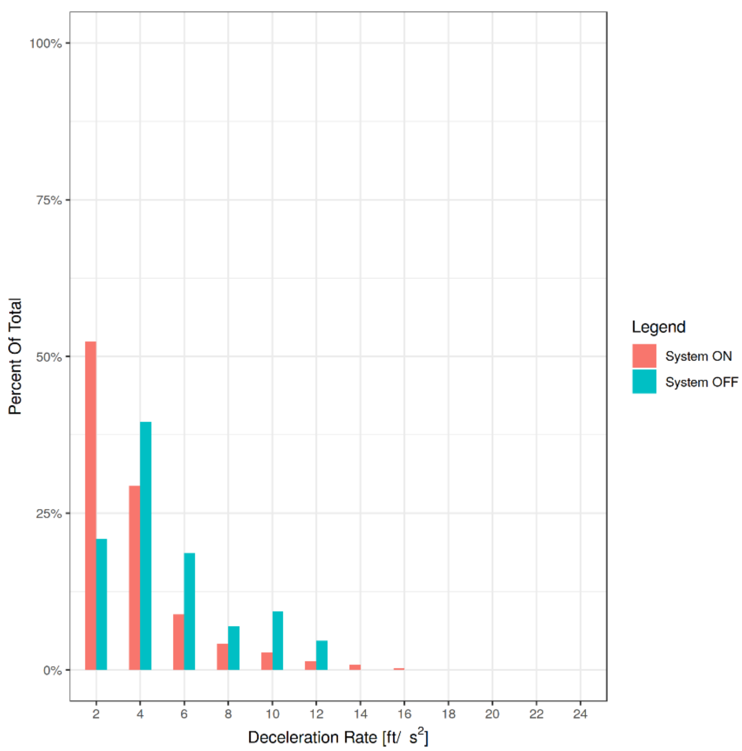


Figure 5.20 McKnight Ave Station. Calculated Deceleration. Reduced Lanes Layouts

On the station at McKnight Ave, as seen in **Figure** 5.20, as was the case on the White Bear Ave location, we observe a noticeable improvement of conditions when the system was online. Again, the trailer displaying the downstream speeds was located a fair distance upstream of the station and as was presented in the 2017 queue frequency graph, less than 30% of the time the queue reached that far and it did it in a much slower pace. The algorithm had enough time to realize the speed drop and warn the drivers a fair distance away from the back of the queue. During all lanes open, the congestion rarely reached that far so no data are available.

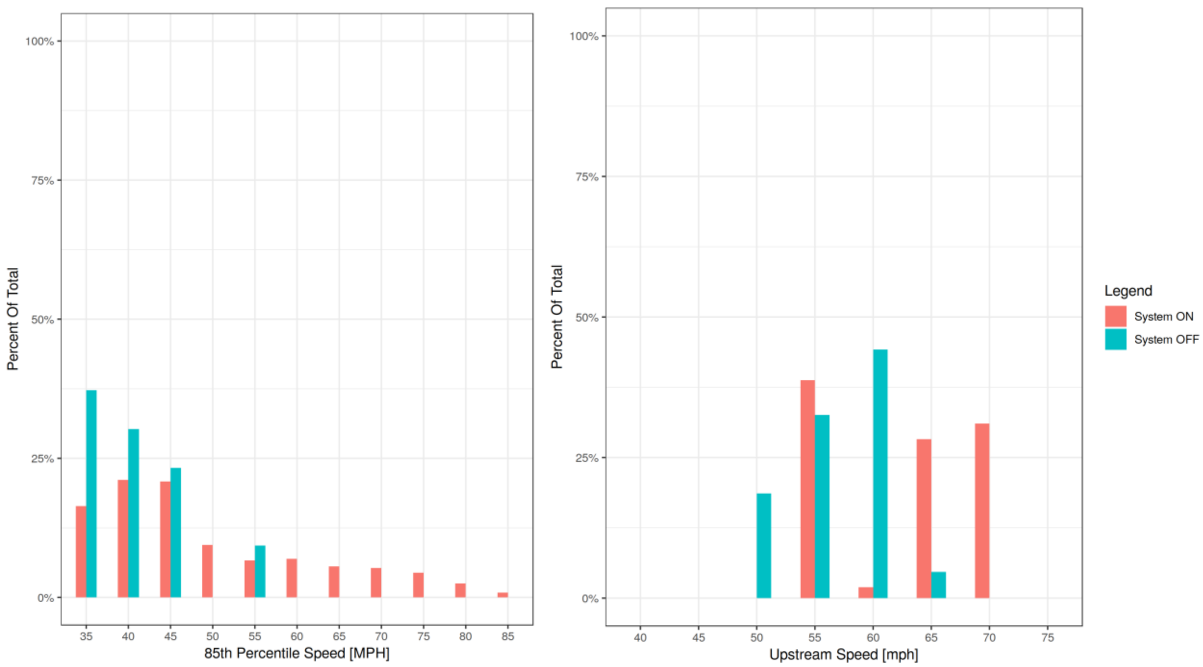


Figure 5.21 McKnight Ave Station. 85th-percentile Speed and Upstream Detector Speed. Reduced Lanes Layouts

Interestingly, from **Figure** 5.21we see that the approach speed to the back of the queue only was a lot higher with the system, observation corroborated by the upstream detector data also. Regardless, the deceleration rates were reduced. This means that drivers were warned about the queue/speed reduction and although they didn't slow down until they were really close to the back of the queue, they performed this slow down through noticeably lower decelerations. This is a very encouraging result in favor of the speed notification system for work zones.

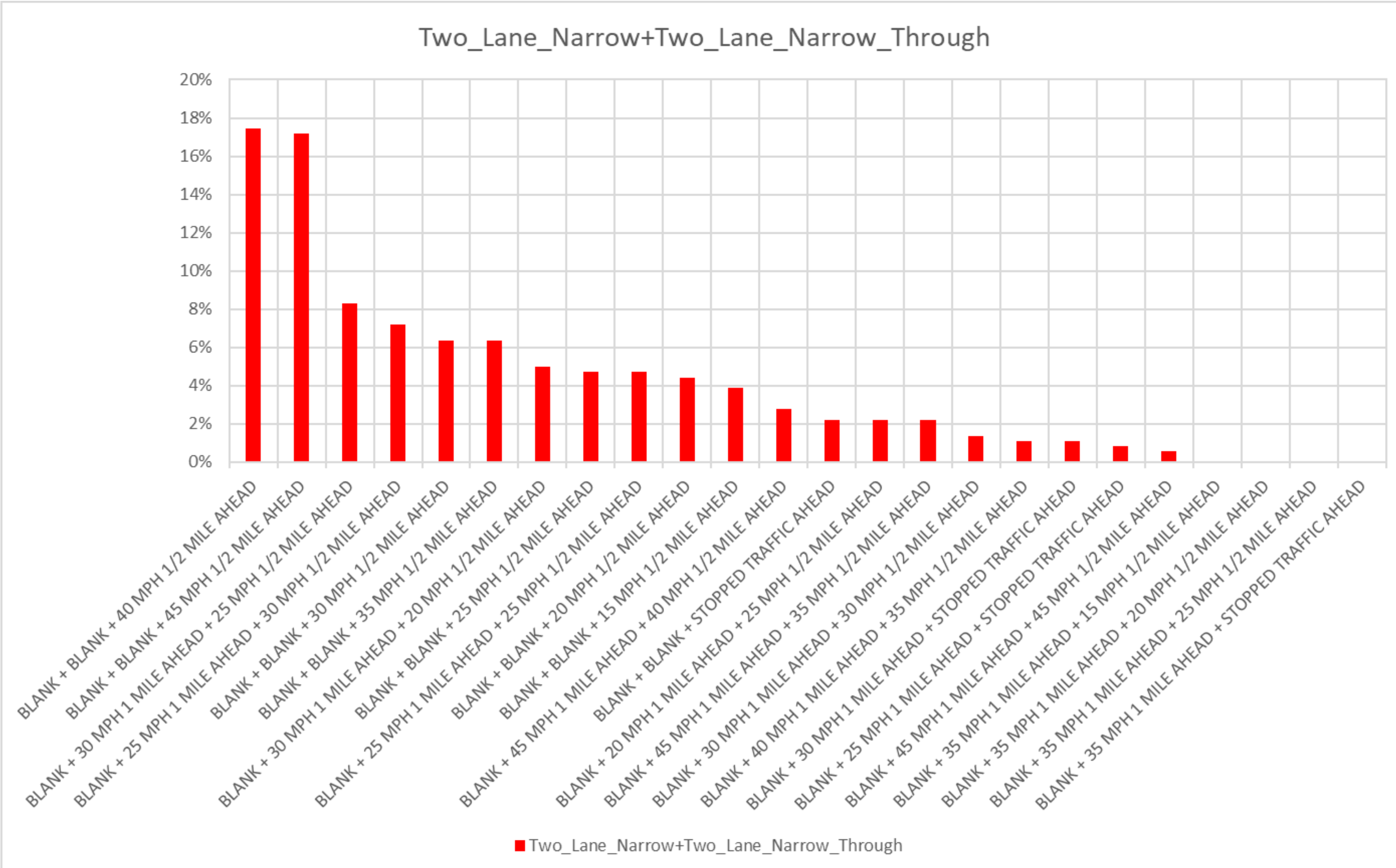


Figure 5.22 McKnight Ave Station Queued Vehicles Message history over last three trailers .

5.5 3M STATION TRAJECTORY ANALYSIS

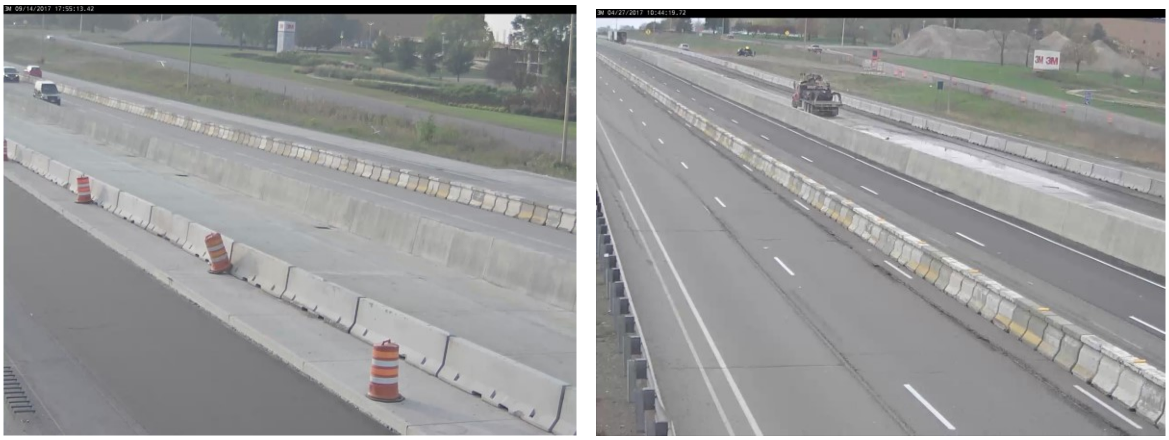


Figure 5.23 3M Station. Reduced Lanes Layouts. 2-Lane, 2-Lane Through only

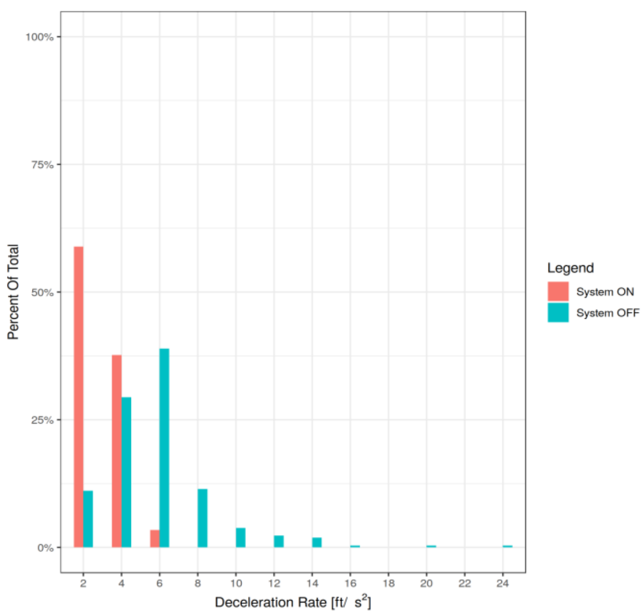


Figure 5.24 3M Station. Calculated Deceleration. Reduced Lanes Layouts

On the station at 3M, as seen in **Figure** 5.24, as was the case on the previous two locations, a noticeable improvement of conditions was observed when the system was online. Again, the trailer displaying the downstream speeds was located a fair distance upstream of the station and as was presented in the 2017 queue frequency graph, less than 30% of the time the queue reached that far and it did it in a much slower pace.

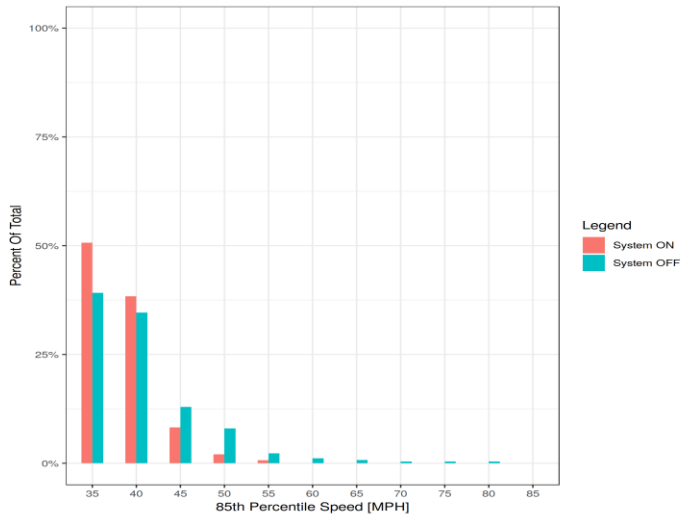


Figure 5.25 3M Station. 85th-percentile Speed. Reduced Lanes Layouts

Similarly to McKnight Ave, from **Figure** 5.25 we see that the approach speed to the back of the queue only changed a little with and without the system. This means that drivers were warned about the queue/speed reduction and although they didn't slow down until they were really close to the back of the queue, they performed this slow down through noticeably lower decelerations. This is a very encouraging result in favor of the speed notification system for work zones.

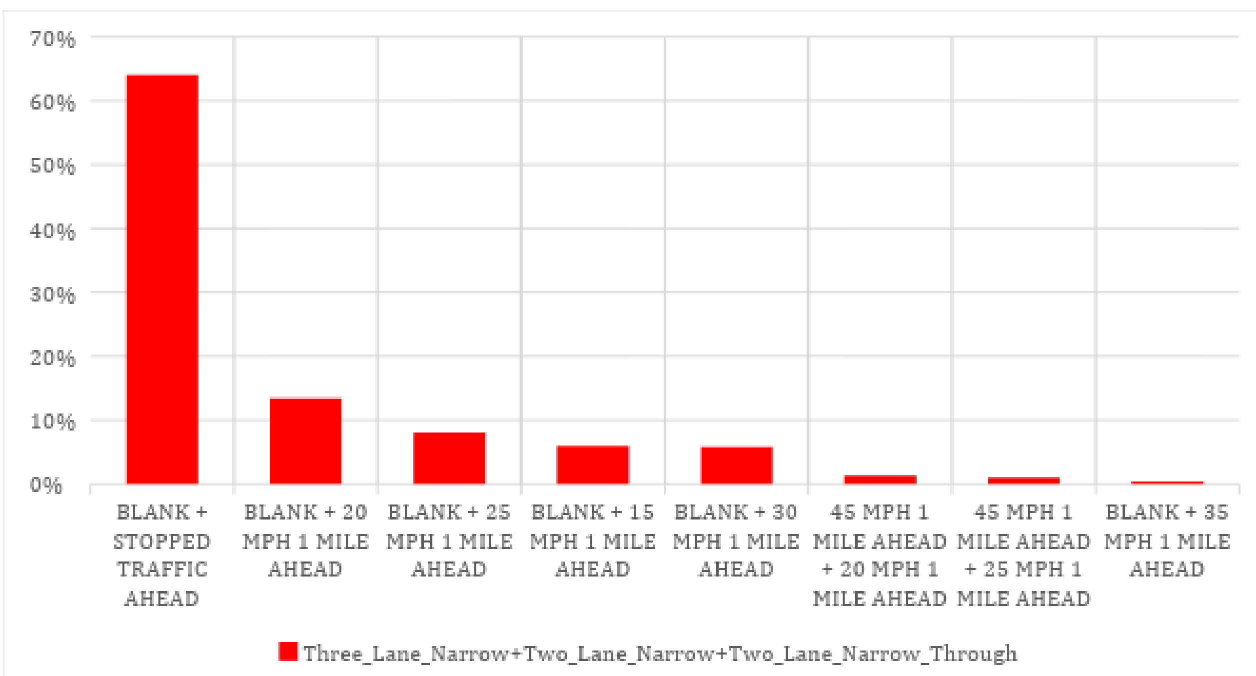


Figure 5.26 3M Station Queued Vehicles Message history over last three trailers

5.6 CENTURY STATION TRAJECTORY ANALYSIS

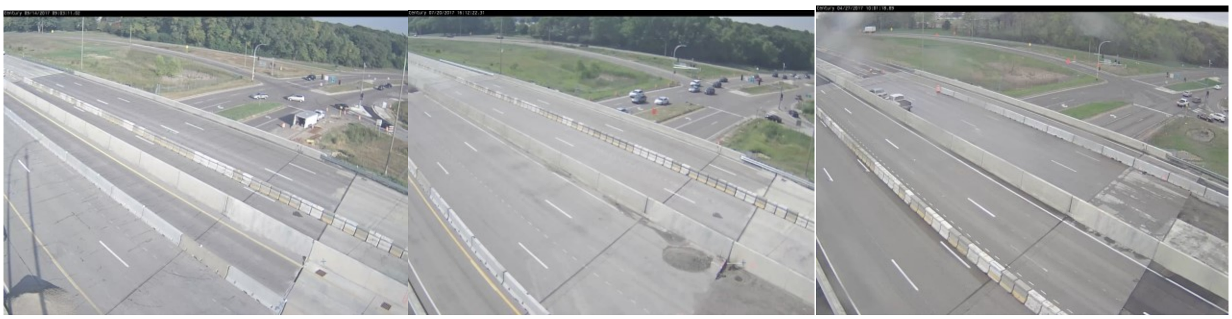


Figure 5.27 Century Avenue Station. Reduced Lanes Layouts. 3-Lane, 2-Lane, 2-Lane Through only

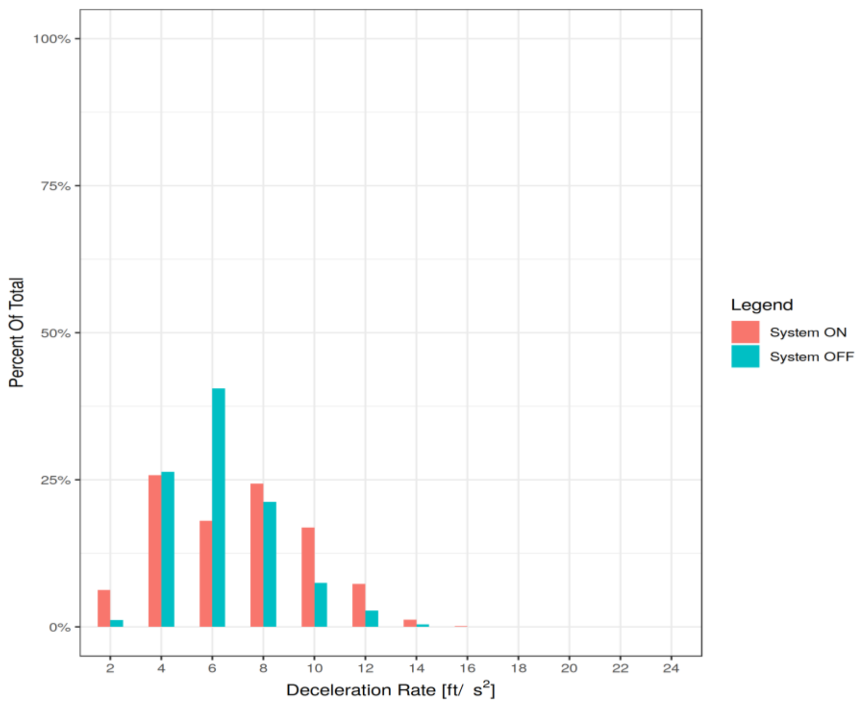


Figure 5.28 Century Avenue Station. Calculated Deceleration. Reduced Lanes Layouts

On the station at Century Ave, as seen in **Figure** 5.28, we observe a small improvement of conditions when the system was online. Rarely, in 2017, the queue reached that far and it did it in a much slower pace. The algorithm had enough time to realize the speed drop and warn the drivers a fair distance away from the back of the queue.

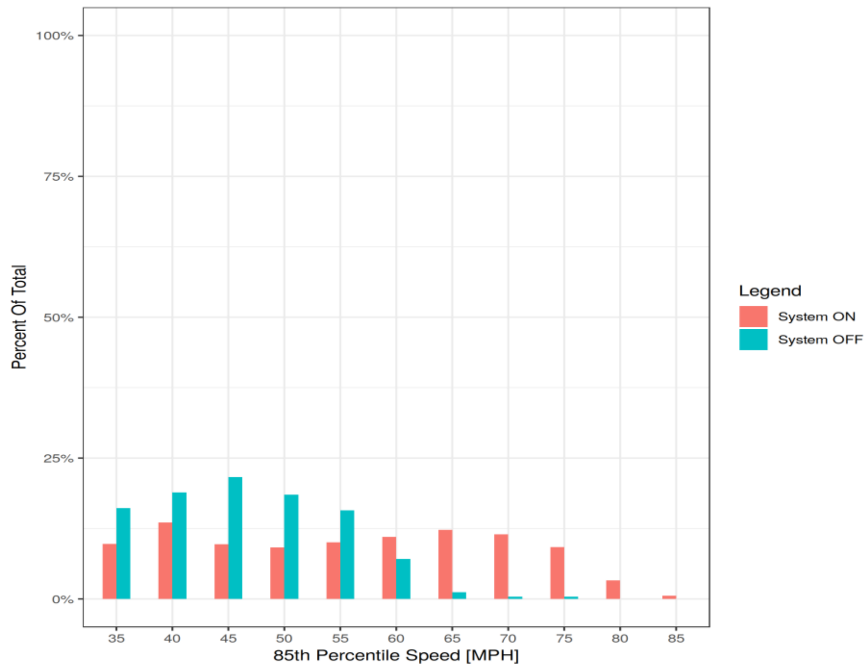


Figure 5.29 Century Ave Station. 85th-percentile Speed. Reduced Lanes Layouts

As seen on **Figure** 5.29 the same phenomenon of higher speed traffic approaching selecting gentler decelerations is observed.

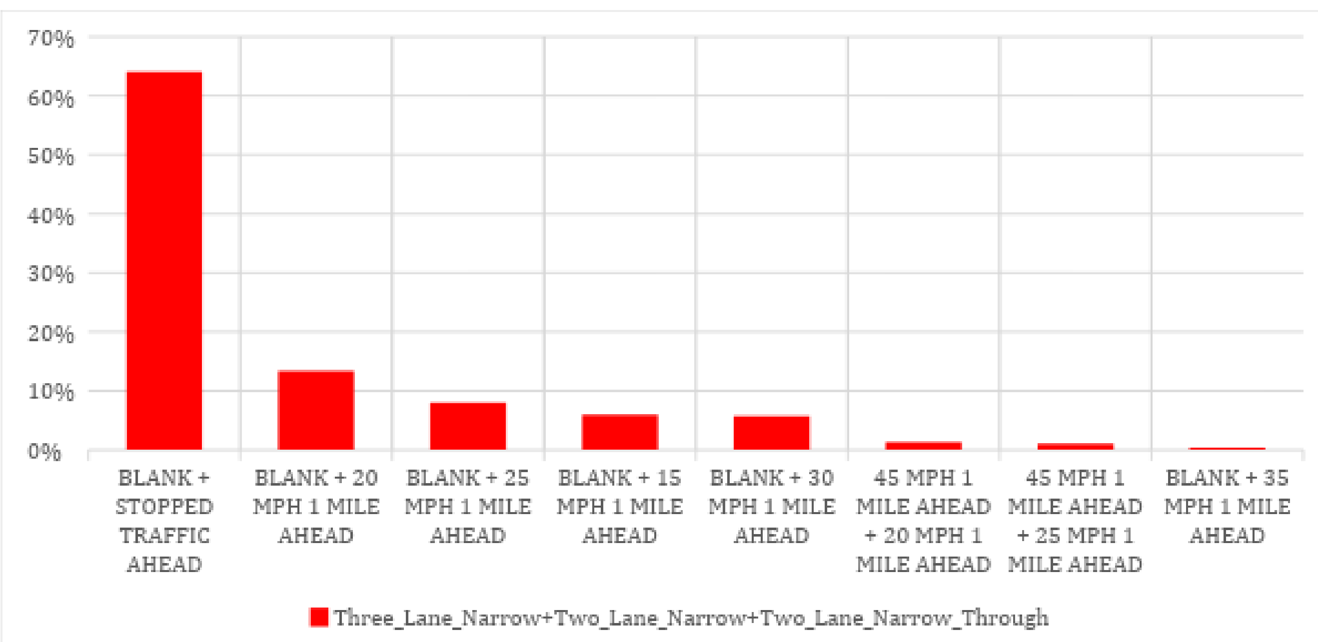


Figure 5.30 Century Ave Station Queued Vehicles Message history over last three trailers

CHAPTER 6: CONCLUSIONS

The primary objective of the project was to quantify the effects of the Speed Notification system on drivers traversing the I-94 work zone east of St Paul during the two years of the resurfacing project. The primary aim of the system, was to notify drivers of the congestion levels downstream and for the possibility of a rapid slowdown to the back of a congestion queue. The hypothesis was that drivers, knowing the speed up to 1 mile downstream will preferably slow down early or at least be alert of the queue and perform smoother decelerations avoiding rear-end collisions.

The research team utilized video data collected downstream of the speed notification signs and at locations where queues were frequently encountered, as well as detector data, and the PCMS message logs. MTO Engineers developed a methodology that utilizes computer-vision-based Trajectory Extraction and used it to analyze 2017 and extract vehicles' deceleration rates when encountering a queue. Based on the analysis of the 2016 data, cameras were repositioned in early 2017 to optimize the performance of the data extraction.

During the first year of the systems operation, based on empirical analysis of the messages generated, the project team identified discrepancies in the Speed Notification Algorithm, mostly in the form of unreasonable or delayed messages. The RTMC never officially disclosed the logic used in the system so it is difficult to know if any changes were implemented during the second year of the system's operation (2017). Regardless, the operation during the 2017 construction season experienced a significant reduction in the earlier identified problematic operation. It is possible that although the algorithm didn't change, the utilized Wavetronix speed sensors MnDOT deployed were providing better speed measurements.

As detailed in Chapter 5, the Speed Notification system resulted in general in beneficial reductions of selected decelerations by the drivers. Especially, in situations where the messages communicated to the drivers were consistent and accurate, reductions of more than 30% in the selected deceleration rates were observed. Unfortunately, several cases where counterproductive or misleading messages were communicated to the drivers, relative increases to the selected deceleration rates were observed.

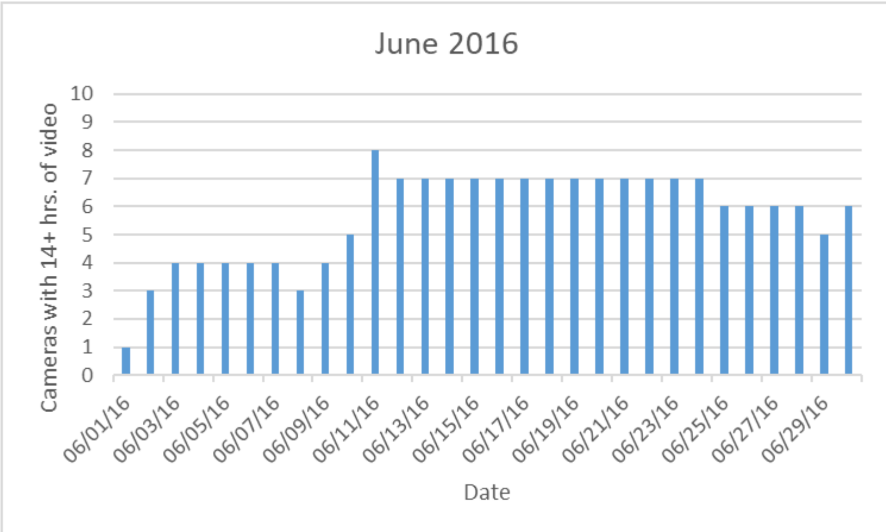
The important observation, stemming from both positive and negative influences, is that the Speed notification system is noticed by the drivers and results in a statistically significant influence in driving behavior. This is much more than many other driver warning systems have ever achieved and it suggests that downstream speed notification, as opposed to advisory speed limits, is an effective traffic control tool. The particular speed estimation and message generation algorithm can be improved to reduce the occurrences of misleading and counterproductive message combination.

REFERENCES

Bernardin, K., & Stiefelhagen, R. (2008). Evaluating multiple object tracking performance: the CLEAR MOT metrics. *Journal on Image and Video Processing*, *2008*, 1.

Jackson, S., Miranda-Moreno, L., St-Aubin, P., & Saunier, N. (2013). Flexible, mobile video camera system and open source video analysis software for road safety and behavioral analysis. *Transportation Research Record: Journal of the Transportation Research Board*, (2365), 90-98.

APPENDIX A: VIDEO DATA AVAILABILITY SUMMARY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Cameras with 14+ hrs. of video
10
9
8
7
6
5
4
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2
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0
06/01/16
06/03/16
06/05/16
06/07/16
06/09/16
06/11/16
06/13/16
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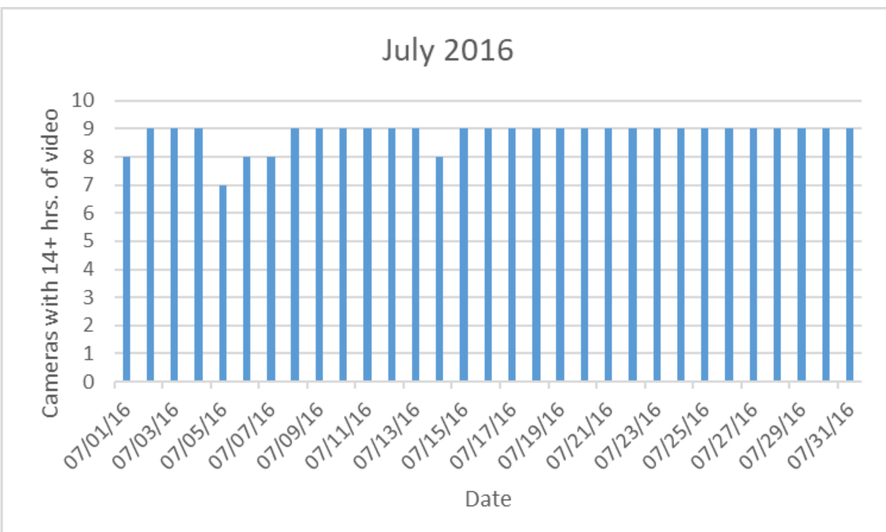
06/29/16
Date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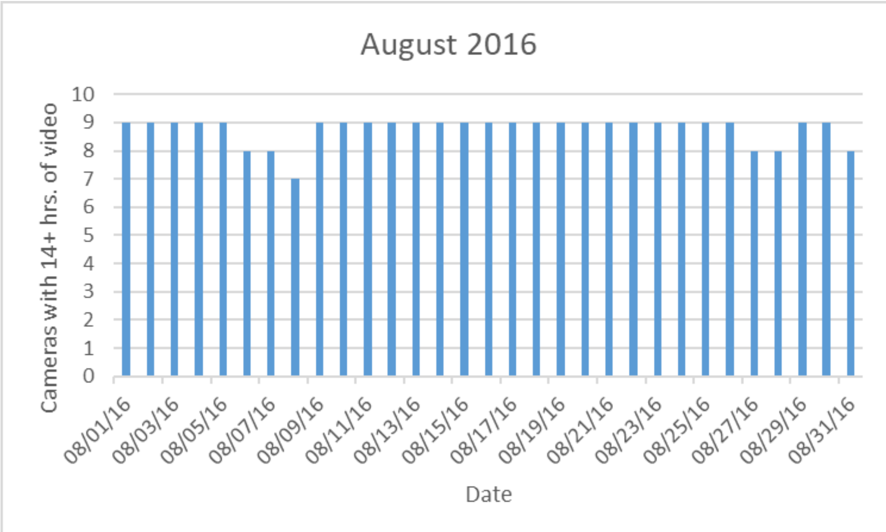
Date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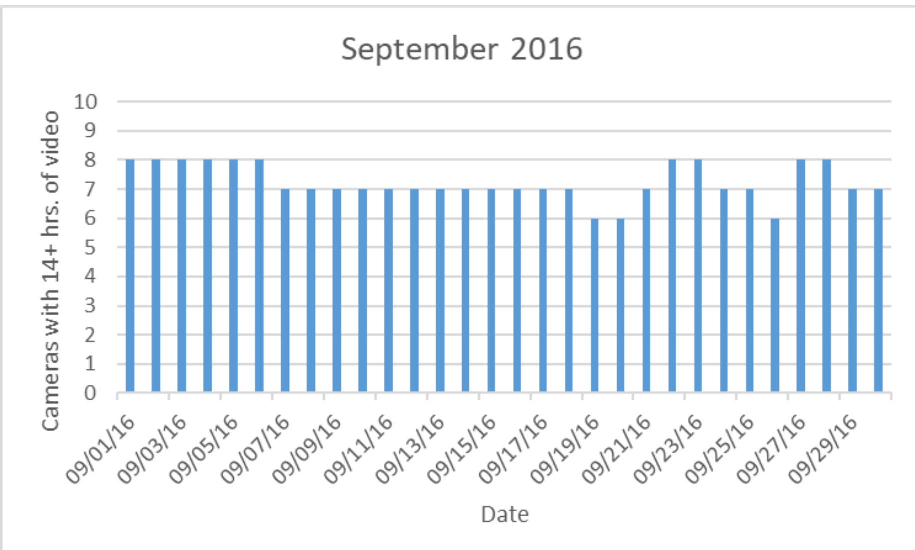
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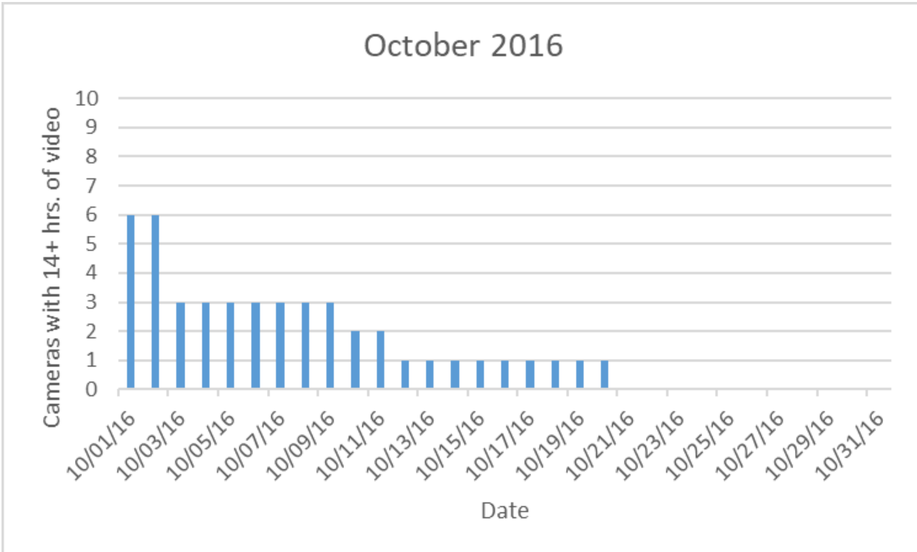
Date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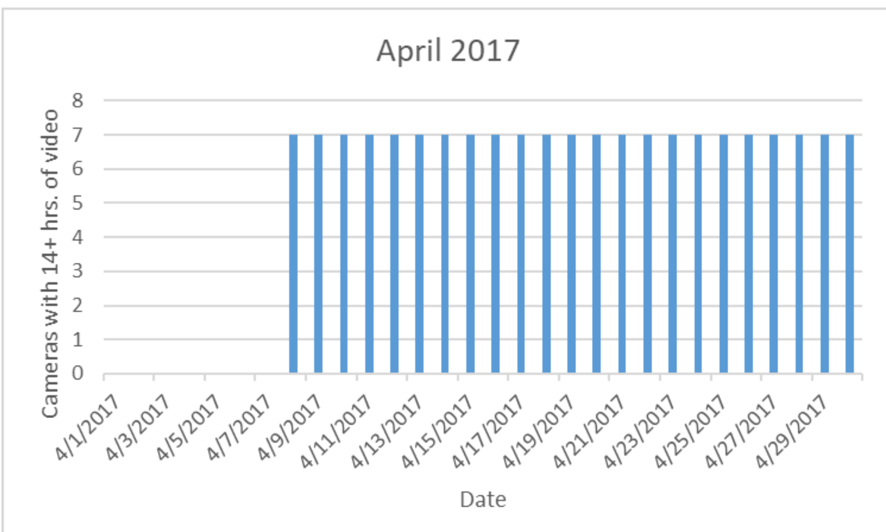
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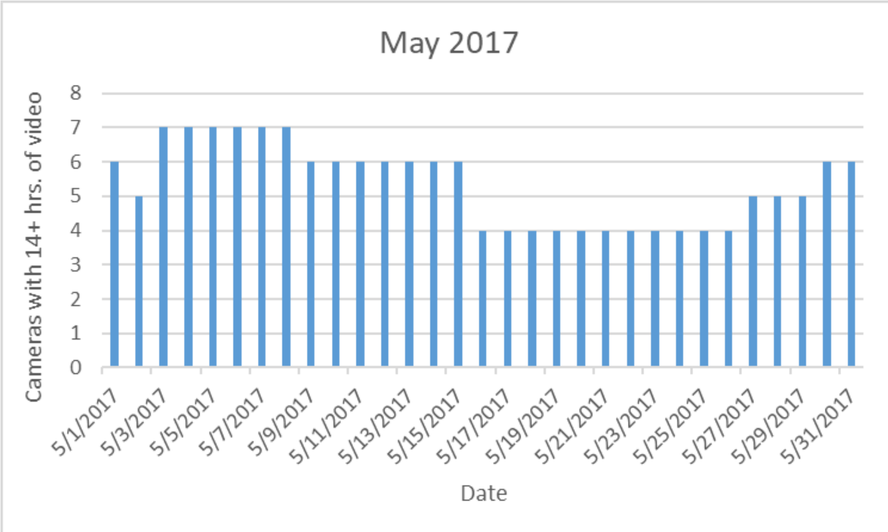
Date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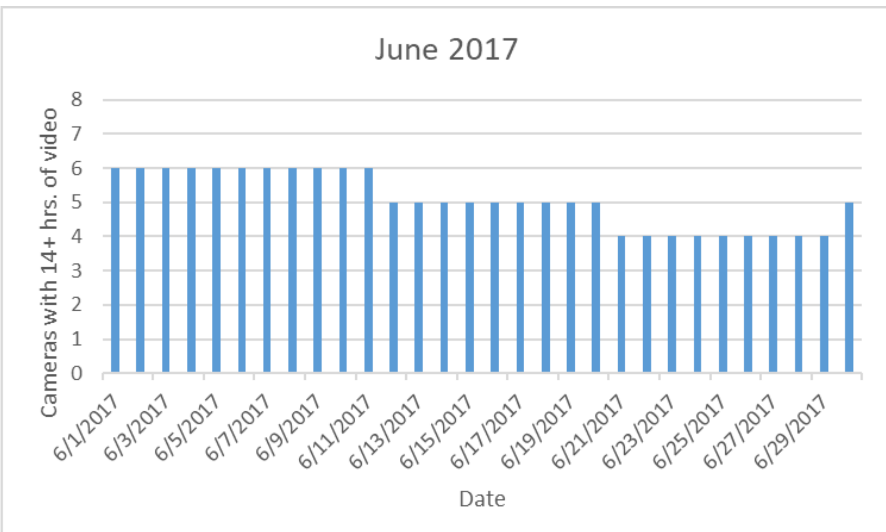
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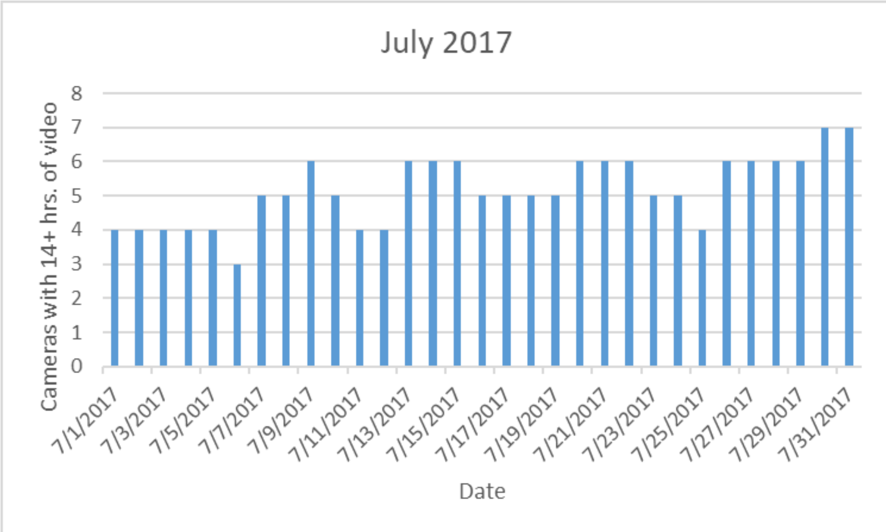
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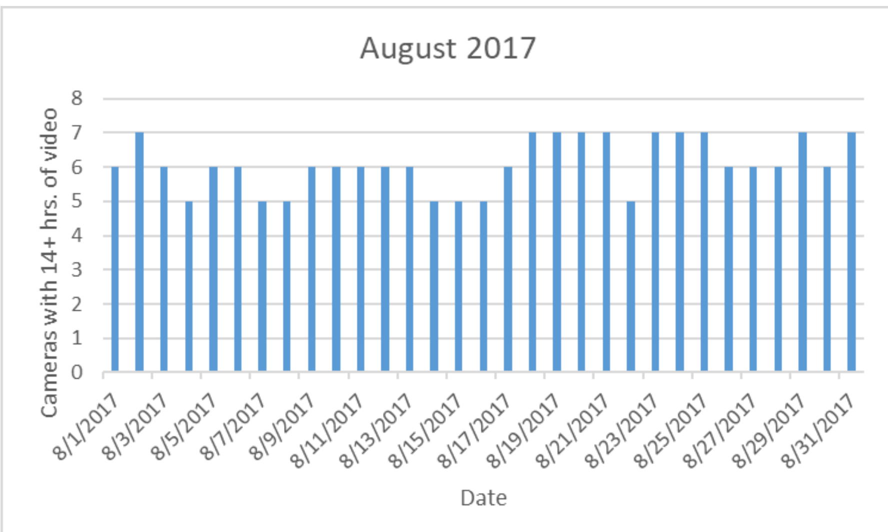
7/31/2017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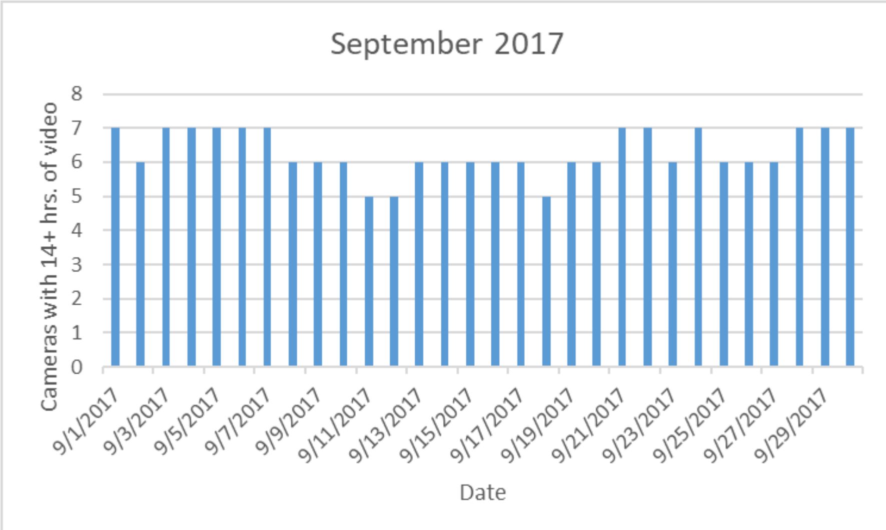

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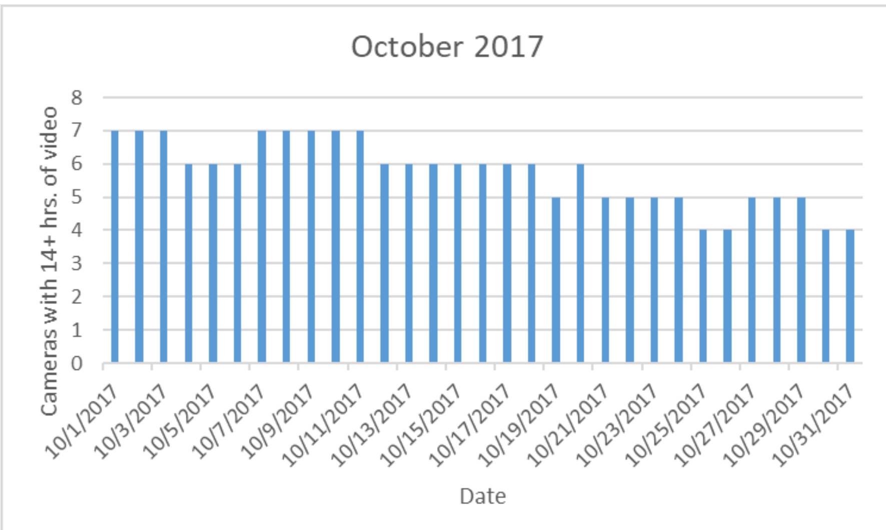

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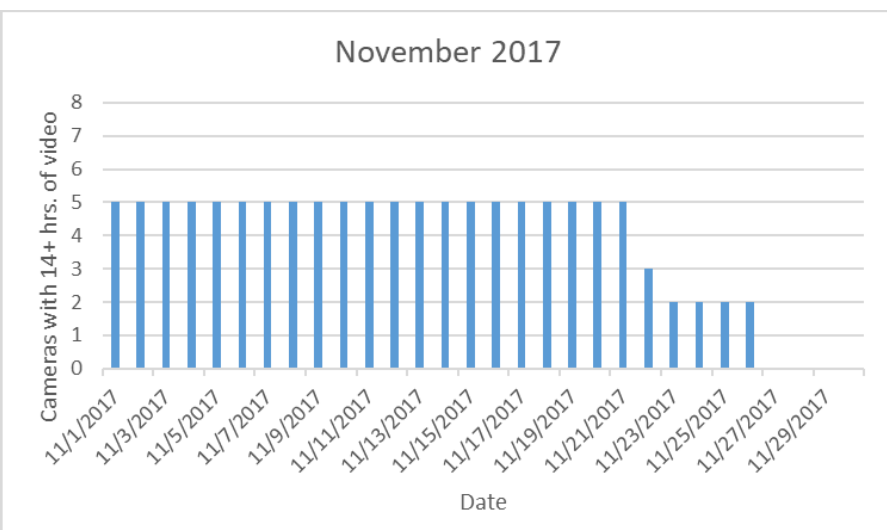


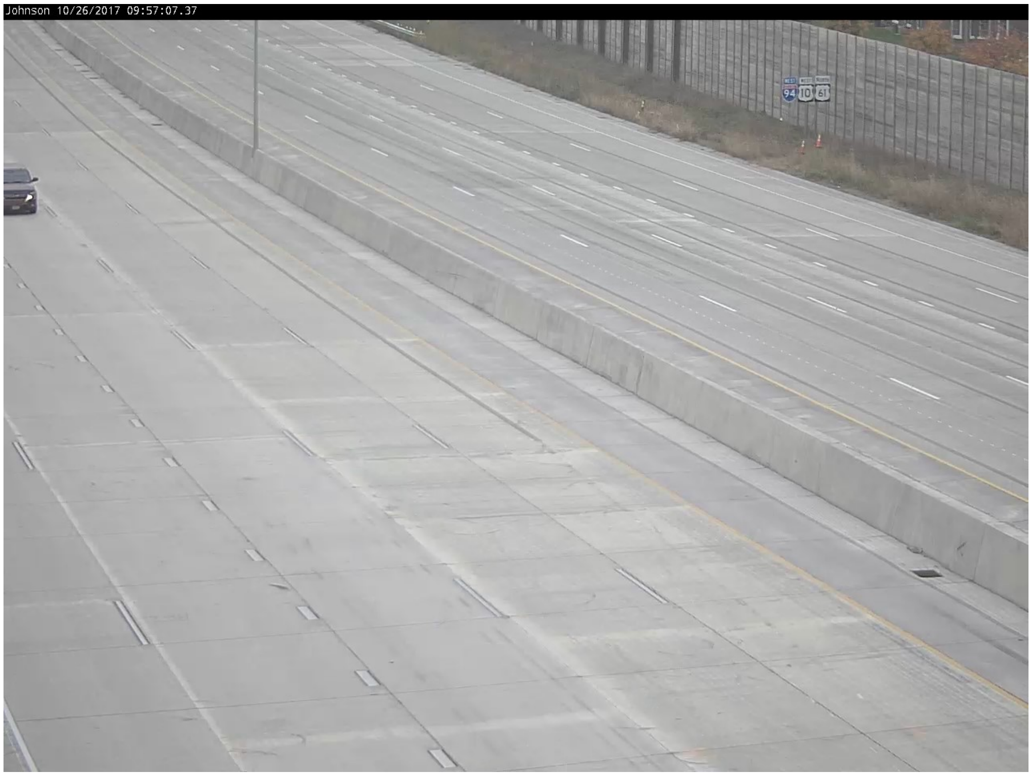
November 2017
Cameras with 14+ hrs. of video
Date

APPENDIX B: LOCATION LAYOUTS WITH PHOTOS

Camera	SS Layout	Name	System Status
Johnson	L001	Four_Lane_Narrow	Both

Camera	SS Layout	Name	System Status
Johnson	L002	Three_Lane_Narrow	On only

Camera	SS Layout	Name	System Status
Johnson	L003	Normal_Road	Both

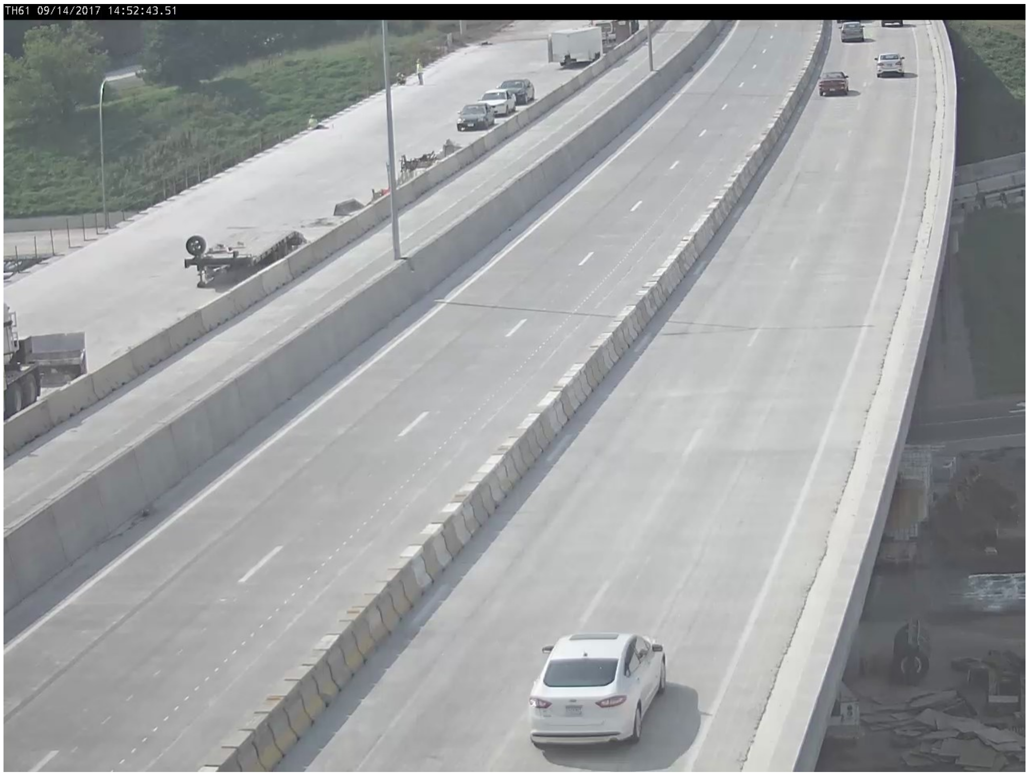


Camera	SS Layout	Name	System Status
Johnson	L004	Four_Lane_Narrow_Double_Barrel	Both

Camera	SS Layout	Name	System Status
Johnson	L006	Two_Lane_Narrow_Through. One_Lane_Narrow_Local	Off only

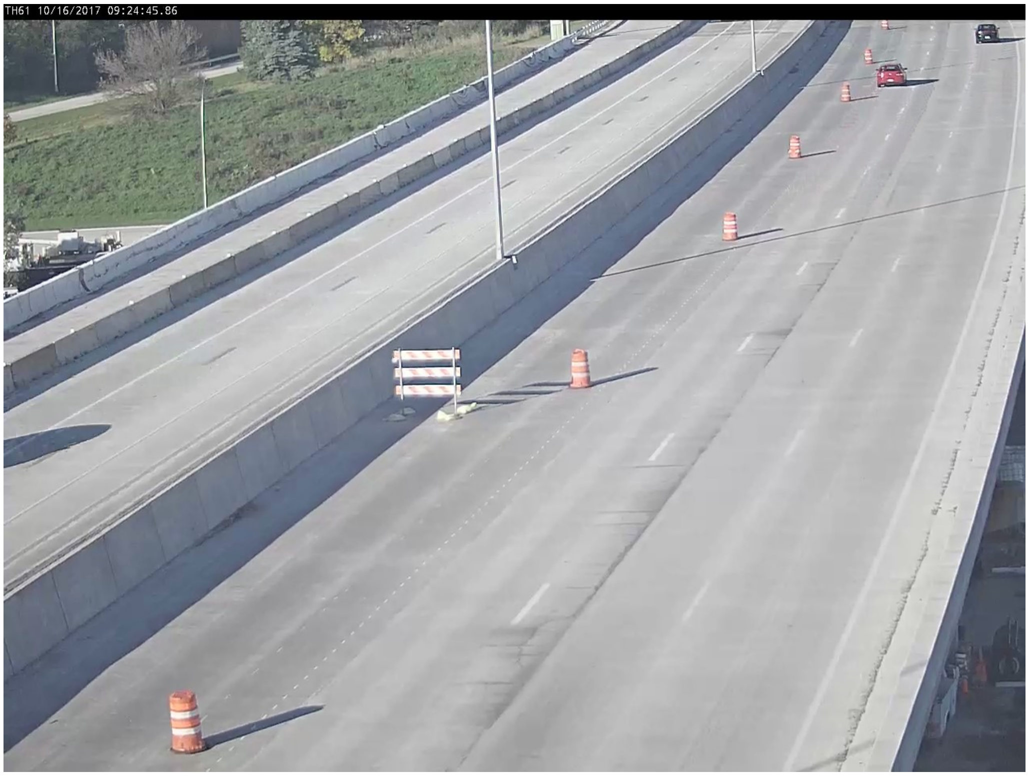
Camera	SS Layout	Name	System Status
TH61	L001	Three_Lane_Narrow	On only

Camera	SS Layout	Name	System Status
TH61	L002	Two_Lane_Narrow	On only



Camera	SS Layout	Name	System Status
TH61	L003	Normal_Road	Both

Camera	SS Layout	Name	System Status
TH61	L004	Three_Lane_Narrow_Right_Cone	Both



Camera	SS Layout	Name	System Status
TH61	L006	Two_Lane_Narrow_Through, One_Lane_Narrow_Local	Off only

Camera	SS Layout	Name	System Status
WhiteBear	L001	Three_Lane_Narrow	On only

Camera	SS Layout	Name	System Status
WhiteBear	L002	Two_Lane_Narrow	On only

Camera	SS Layout	Name	System Status
WhiteBear	L006	Two_Lane_Narrow_Through, One_Lane_Narrow_Local	Off only

Camera	SS Layout	Name	System Status
WhiteBear	L007	One_Lane_Narrow_Through, One_Lane_Narrow_Local	Off only

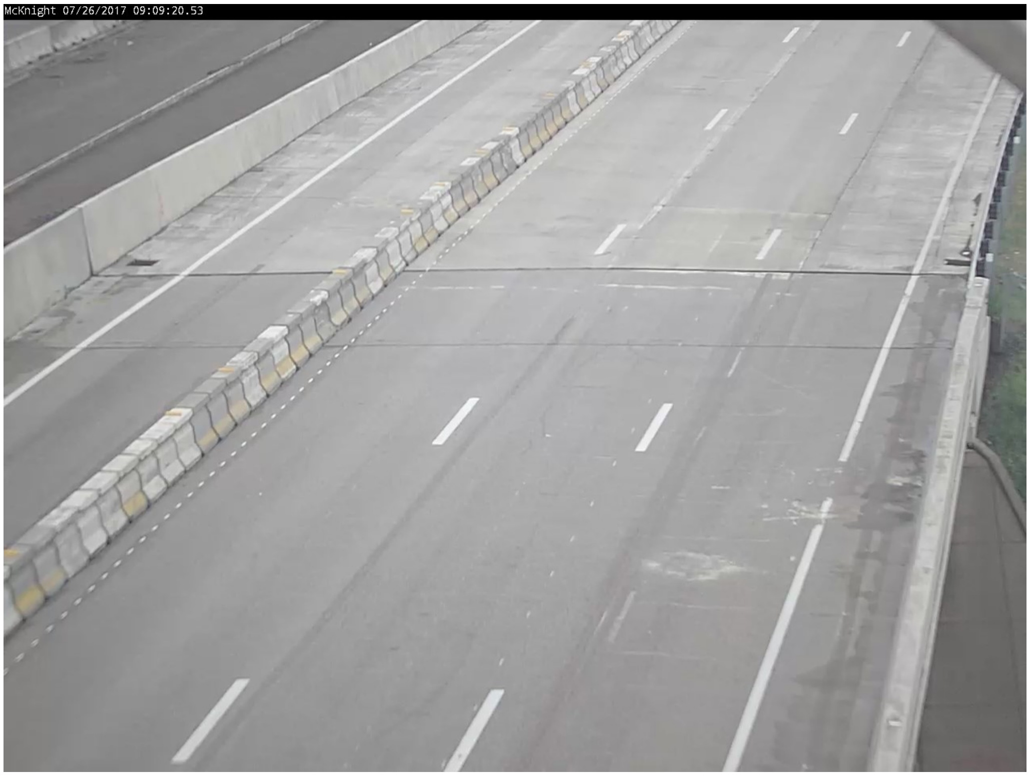
Camera	SS Layout	Name	System Status
Ruth	L001	Three_Lane_Narrow	On only

Camera	SS Layout	Name	System Status
Ruth	L002	Two_Lane_Narrow	On only

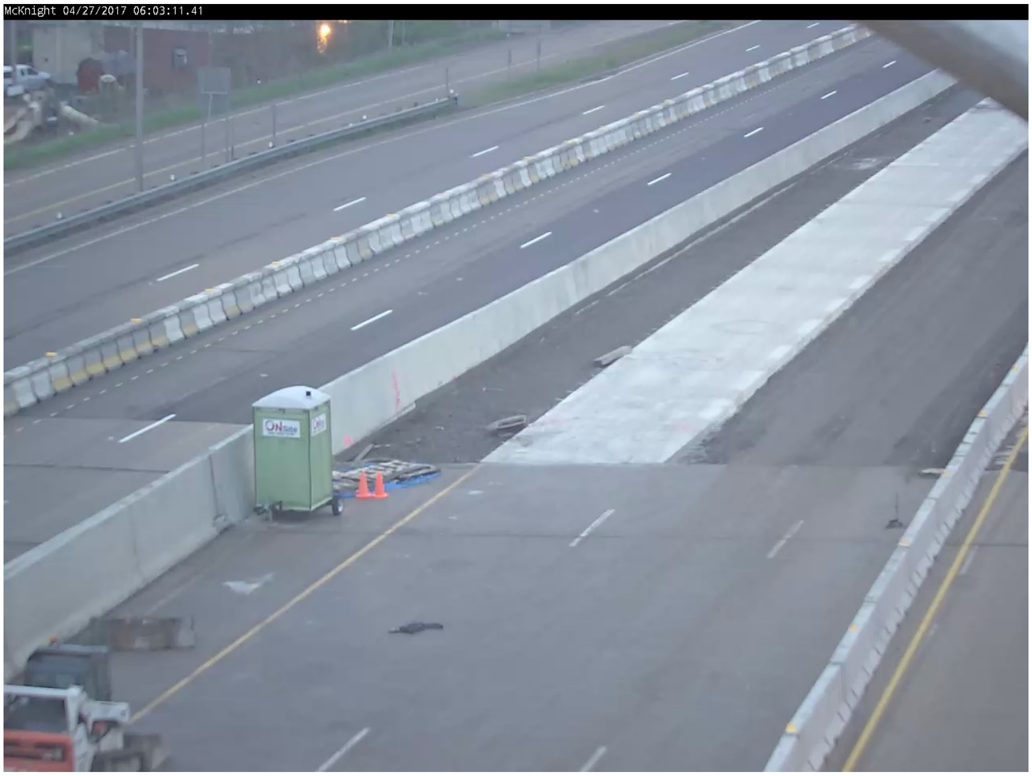
Camera	SS Layout	Name	System Status
Ruth	L007	Two_Lane_Narrow_Through, One_Lane_Narrow_Local	Off only

Camera	SS Layout	Name	System Status
McKnight	L001	Two_Lane_Narrow	On only

Camera	SS Layout	Name	System Status
McKnight	L002	Three_Lane_Narrow	On only



Camera	SS Layout	Name	System Status
McKnight	L004	Two_Lane_Narrow_Through	Off only



Camera	SS Layout	Name	System Status
3M	L001	Three_Lane_Narrow	On only

Camera	SS Layout	Name	System Status
3M	L002	Two_Lane_Narrow	Both

Camera	SS Layout	Name	System Status
3M	L005	Two_Lane_Narrow_Through, One_Lane_Narrow_Local	Off only

Camera	SS Layout	Name	System Status
Century	L001	Three_Lane_Narrow	On only

Camera	SS Layout	Name	System Status
Century	L002	Two_Lane_Narrow	Both

Camera	SS Layout	Name	System Status
Century	L006	Two_Lane_Narrow_Through, One_Lane_Narrow_Local	Off only

Camera	SS Layout	Name	System Status
Century	L007	One_Lane_Narrow_Through, One_Lane_Narrow_Local	Off only


Century 04/27/2017 13:02:16.51