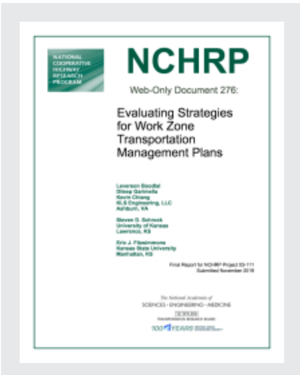

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Evaluating Strategies for Work Zone Transportation Management Plans

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Final Report for NCHRP Project 03-111
Submitted November 2019

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed, and implementable research is the most effective way to solve many problems facing state departments of transportation (DOTs) administrators and engineers. Often, highway problems are of local or regional interest and can best be studied by state DOTs individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation results in increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

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NCHRP Web-Only Document 276: Evaluating Strategies for Work Zone Transportation Management Plans is presented in association with *NCHRP Research Report 945: Strategies for Work Zone Transportation Management Plans*.

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Summary

In the United States, between 2010 and 2018, an average of 679 people died and about 36,750 people were injured each year as a result of motor vehicle crashes in work zones (National Work Zone Safety Information Clearinghouse). It is also estimated that work zones account for nearly 24% of nonrecurring traffic delays.

Reducing these crashes and traffic delays—and their negative effects on lives and the economy—requires a better understanding of the effectiveness of work zone transportation management strategies. **Transportation management plans** (TMPs) are a set of coordinated strategies designed to help agencies achieve their work zone projects goals related to traffic mobility, efficient system operation, motorists and workers safety, and other operational targets.

State Departments of Transportation (DOTs) and other transportation agencies currently develop and implement TMPs, which typically involve coordinated strategies related to temporary traffic control (TTC), transportation operations (TO), and public information. TMPs also help road users traverse work zones safely by understanding project effects, alternatives, scheduling, and anticipated benefits.

State DOT practices, however, vary considerably with respect to what the agency considers when selecting strategies to integrate into a TMP. Additionally, practitioners can be uncertain of the effectiveness of their strategies and the value of their economic benefit. As a result, transportation agencies may not fully understand the application, safety/operational effectiveness, or the cost-efficiency of their TMP decisions.

The objectives of this project, **NCHRP 03-111: Effectiveness of Work Zone TMP Strategies**, are:

- Provide information on a wide range of strategies for work zone practitioners in the form of a "Guidebook."
- Conduct field evaluations of three selected TMP strategies: truck lane restrictions, ramp metering, and reversible lanes.

The guidebook is published as *NCHRP Research Report 945* and is available on the TRB website. The guidebook provides a compendium of current knowledge on work zone strategies, including suggestions on when to use each and its benefits, effectiveness, related technical issues, design requirements, state of the practice, and cost.

This report focuses on the field evaluation portion of the project, results of which are discussed below.

Truck Lane Restrictions. A field evaluation of the effectiveness of work zone truck lane restrictions (TRUCKS USE LEFT LANE) was conducted at three work zone sites in Michigan.

- **Truck use of the left lane** for all sites combined increased by 234.96% while decreasing by 59.36% in the right lane.
- **Average passenger car and truck speeds** showed mixed results with increases and decreases at each test site. However, across the three study sites, the overall average truck speeds reduced by approximately 3 mph (5%) with the truck lane restrictions.
- **The comparisons of the headways** of vehicles on the left lane (lane trucks were restricted to) of the freeway during *with* and *without* conditions improved. Lower headways (less than 300 feet) improved between 19% and 66%.
- **Headways of truck following a car or truck** increased on the left lane (the lane trucks were restricted to).

Conditions most appropriate for truck lane restrictions are roadways with two or more lanes in each direction and interchanges spaced more than two miles apart with low ramp volumes and truck percentages between 10% and 25% of the total main line traffic stream.

Ramp Metering. The effectiveness this strategy was evaluated at two work zone sites in the first full-scale deployment of work zone ramp metering in the United States. Two ramp metering scenarios were implemented during the study period—fixed- and variable-cycle lengths.
The evaluation found ramp metering had a positive effect on the following:

- **Vehicle speeds on the mainline.** Overall, under saturated conditions, fixed-cycle length ramp metering performed slightly better than variable-cycle length ramp metering with speeds increasing 8.6 mph and 5.18 mph, respectively, when compared to baseline conditions. When the mainline was less than 80% saturated, variable-cycle length ramp metering performed better than fixed-cycle length ramp metering. In each scenario, the left lane showed the larger increase as fewer vehicles attempted to merge laterally.
- **Vehicle travel times**. Fixed-cycle length ramp metering performed slightly better than variable-cycle length ramp metering with travel time improvements greater than 20%. When the mainline is less than 80% saturated, variable-cycle length ramp metering performed better than fixed-cycle length ramp metering with travel time improvement in excess of 60%.
- **Ramp metering did not consistently affect vehicle headways** at the merging areas of ramps and the mainline. The minimum average headway was 2.4 seconds.

- **Driver compliance rates for fixed and variable-length ramp metering** ranged between 60% and 90% respectfully, absent any type of enforcement.
- **A critical design feature for ramp metering** is to set the ramp metering to begin at least 15–30 minutes prior to the time of saturation. Traditional ramp metering-design volume criteria cannot accommodate work zone conditions.
- **Recommended total lane/ramp vehicles** should not be greater than 1,600 vehicles per hour (ramp volumes should not exceed 400–600 vehicles per hour).
- For maximum effectiveness, **traffic volumes should be close to 1,400 combined** vehicles per hour per lane (vphpl), with ramp volumes below 600 vphpl.

Reversible Lanes. The effectiveness of using reversible lanes as a work zone strategy was evaluated at three sites—two in Michigan and another in Minnesota:

- **Vehicle speeds on the mainline were generally maintained** across all test sites.
- **Travel times were shorter**. The *t*-test results indicated using reversible lanes decreased travel time for most of the time periods analyzed. On average, travel time improved across all sites ranged between 5.6% and 15%.
- On occasion, **vehicle headways in the reversible lane configuration decreased** because of increase in traffic volumes; however, the minimum average headway was 2.7 seconds.
- Key to a successful reversible lane operation is **understanding the traffic flow pattern**, daily and weekday and knowing when to change over the lanes. Operation must be flexible enough to adjust to changes in demand.
- The **reversible lane does not carry less traffic than other lanes** as previously thought, with a maximum traffic flow per lane from 1,600 to 2,250 vphpl.
- The **capacity reduction factor** for reversible lane operation appears to be 0.90 to 1.20, the latter occurring in cases where the reversible lane operation is within barriers and not affected by ramps and other merging traffic.
- **The number of crashes** were higher when compared to a non-work zone condition, but less than expected for a work zone condition. Advanced signs and pavement markings on the approach to the taper will improve the safety/operation of the reversible lane.

1.0 Introduction

Periodic work zones are necessary to build, maintain, rehabilitate, enhance, and reconstruct this nation's roadway network. Over the course of one year, it was estimated that 26.5% of the National Highway System (NHS) has at least one day with a work zone in place. In the peak summer months, it is estimated that 7.9% of the NHS has a work zone in place on any given workday (*1*).

1.1. Work Zones' Effect on Safety

Unfortunately, work zones can mean daily changes in traffic patterns, narrowed rights-of-way (ROW), and other construction activities that create a combination of factors resulting in crashes. According to the National Work Zone Safety Information Clearinghouse, from 2010 through 2018, an average of 679 people died each year as a result of crashes in work zones.. Table 1 shows the work zone fatality and injury data for the years 2013–2017 (*2*).

Table 1. Work zone crash facts—fatalities and injuries.

Year	Total Work Zone Fatalities	Total Work Zone Injuries	Total Work Zone Crashes
2010	586	36,000	87,000
2011	590	39,000	91,000
2012	619	30,000	76,000
2013	593	25,000	68,000
2014	670	31,000	89,000
2015	718	35,000	97,000
2016	782	61,000[a]	158,000[a]
2017	809	37,000[a]	94,000[a]
2018	755	NA	NA
Average	**680**	**36,750**	**95,000**

NOTE:
[a]NHTSA has redesigned the sampling process used to compute these estimates. Therefore, 2016 and later data are not directly comparable to data from 2015 and before. Data for injuries and crashes greater than 500 have been rounded to the nearest 1,000 and values less than 500 have been rounded to the nearest 100 to reflect the level of uncertainty associated with these estimates. NA = not available.

Additionally, work zone crashes occur in a constrained driving environment, cause congestion and excessive delays. Estimates are that work zones crashes account for 10% of overall congestion and 24% of nonrecurring freeway delays nationwide (*4*).

Reducing these crashes and delays—and their negative effects on lives and the economy—requires a better understanding of the effectiveness of work zone transportation management strategies. **Transportation management plans** are a set of coordinated strategies designed to help agencies achieve their work zone projects goals related to traffic mobility, efficient system operation, motorists and workers safety, and other operational targets.

State DOTs and other transportation agencies currently develop and implement TMPs, which typically involve coordinated strategies related to TTC, TO, and public information. TMPs also help road users traverse work zones safely by understanding project effects, alternatives, scheduling, and anticipated benefits.

State DOT practices, however, vary considerably with respect to what the agency considers when selecting strategies to integrate into a TMP. Practitioners can be uncertain of the effectiveness of their safety solutions and the value of their economic benefit. As a result, transportation agencies may not understand the application, its effectiveness, or the cost-efficiency of their TMP decisions.

1.2. Project Objective

The objectives of this project, ***NCHRP 03-111: Effectiveness of Work Zone Transportation Management Plan Strategies***, are to:

- Provide information on a wide range of strategies for work zone practitioners in the form of a "Guidebook."
- Conduct field evaluations of three selected TMP strategies: truck lane restrictions, ramp metering, and reversible lanes.

1.3. Report Purpose

This report focuses on the field evaluation of the following three strategies - truck lane restrictions, ramp metering, and reversible lanes.

The guidebook is published as *NCHRP Research Report 945* and is available on the TRB website. The guidebook provides a compendium of current knowledge on work zone strategies, including suggestions on when to use each and its benefits, effectiveness, related technical issues, design requirements, state of the practice, and cost.

1.4. Report Organization

This report contains nine chapters.

Following this Introduction, Chapter 2 provides an overview of the guidebook, which, as noted, is provided separately as a standalone document.

Chapter 3 presents the results of a practitioner survey intended to solicit information and perspectives from state DOTs on how they manage a variety of work zone challenges.

Chapter 4 presents the methodology for selecting strategies for field evaluation and the final list of treatments for field evaluation. Appendix A provides the survey tool used to solicit state DOT input.

Chapter 5, 6, and 7 presents field evaluation results of three strategies: truck lane restrictions, ramp metering, and reversible lanes.

Chapter 8 provides a summary of findings relating to the three field evaluations.

2.0 TMP Strategy Guidebook

Although there is a wealth of information, it is scattered among published research, DOT handbooks, manuals, plans, as well as unpublished documentation. This project developed a TPM Strategy Guidebook, a resource that synthesizes useful knowledge from all these diverse sources to create a work zone guidebook. The guidebook provides a compendium of current knowledge on work zone strategies, including suggestions on when to use, benefits, effectiveness, technical issues, design requirements, state of the practice, and cost.

The guidebook is published as *NCHRP Research Report 945* and is available on the TRB website.

2.1. Guidebook Contents and Organization

Many work zone management strategies can be used to minimize traffic delays, improve mobility, maintain or improve motorist and worker safety, and complete roadwork in a timely manner. The strategies presented and reviewed in the guidebook are grouped according to the FHWA TMP classification under the following categories:

1. TO
   - Work zone safety management strategies
   - Corridor/network management (traffic operations) strategies
   - Traffic/incident management and enforcement strategies
   - Demand management strategies
2. TTC
   - Control strategies
   - Project coordination
   - Alternative contracting and construction strategies
   - Traffic control devices (TCD)
3. Public awareness
   - Motorist information strategies
   - Public awareness strategies

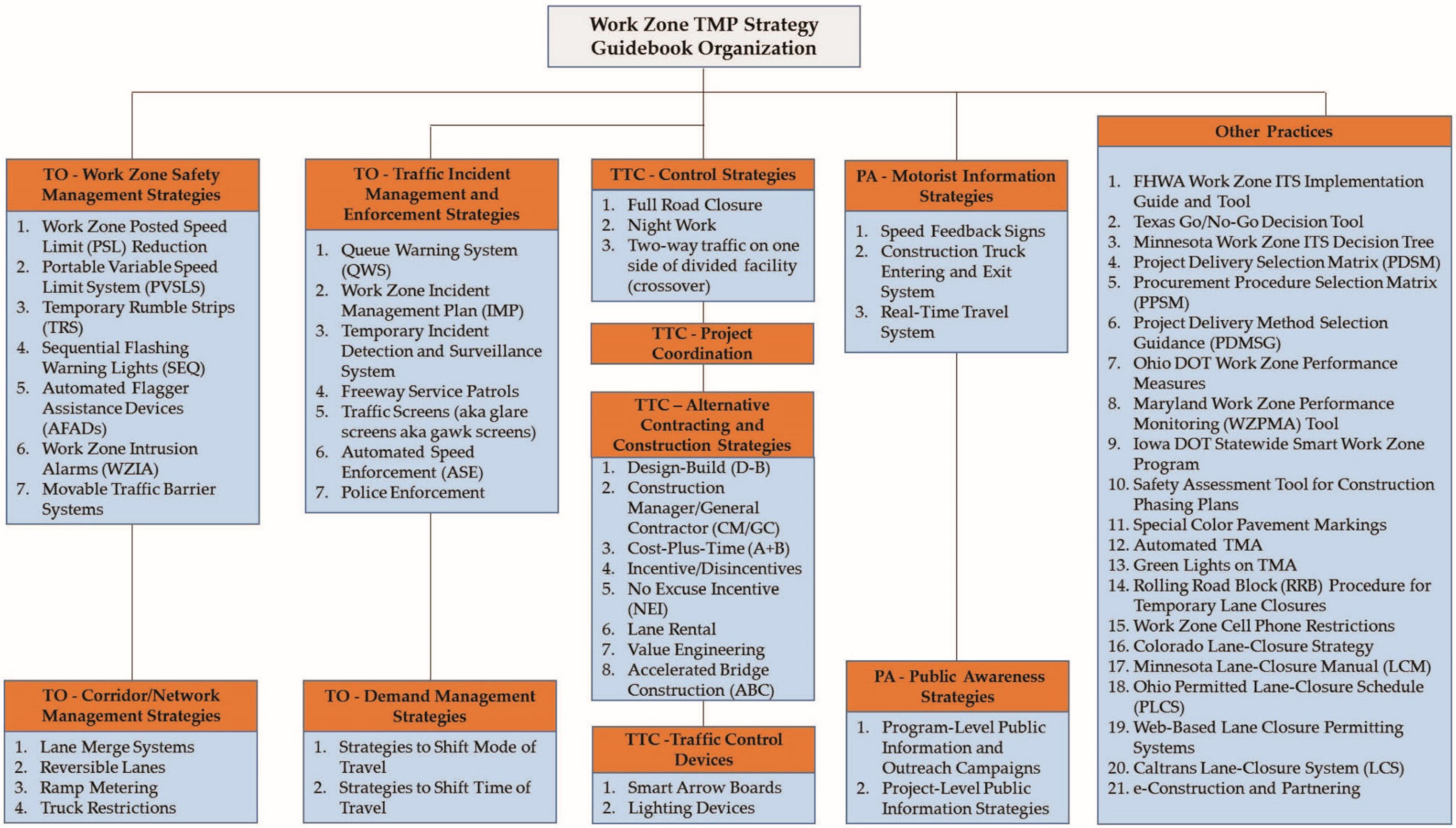
The guidebook devotes a section to each of the above-cited major categories. Figure 1 shows how the strategies are grouped to help users find relevant practices. The entry for each strategy includes:

- **Description.** Provides short overview and description.
- **When to Use.** Discusses conditions for use.
- **Benefits.** Discusses typical strategy benefits in terms of improving safety and/or mobility.
- **Expected Effectiveness**. Describes known effectiveness based on field studies.

- **Crash Modification Factor (CMF)**. Presents estimated and known CMFs based on information presented in NCHRP Report 869 (*1*).
- **Implementation Considerations**. Discusses how the strategy functions and if there are any installation concerns, potential difficulties, maintenance issues, etc.
- **Design Features / Requirements.** Provides information on the appropriate design criteria, and hardware and software requirements if any.
- **State of the Practice**. Provides examples where a strategy has been used with special provisions and standard typical drawings, as applicable.
- **Cost**. Reviews estimated installation cost.
- **Resources.** Presents related resources and cited materials.

In addition to the category and subcategory designations, strategies are cross-referenced as shown in Appendix B. The cross-references allow practitioners to identify these strategies based on traffic conditions in the work zone, the type of roadway involved, geographic or demographic characteristics, and when in the project life-cycle stage, they are used.

Another category—best practices—was introduced to account for those strategies that do not have a measurable value for effectiveness. The best practices include emerging technologies, decision-making tools, case studies and successful policies and procedures of few state DOTs.



NOTE: Caltrans = California Department of Transportation; DOT = Department of Transportation; ITS = intelligent transportation system; PA = public awareness; TMA = truck-mounted attenuator; TMP = transportation management plans; TO = transportation operation; TTC = temporary traffic control.

Figure 1. Guidebook strategy organization.

3.0 Survey Results Regarding the Use and Effectiveness of Individual TMP Strategies

This chapter describes the survey used for this project and summarizes its primary findings.

3.1. Methodology

An electronic survey was distributed to state DOTs work zone coordinators and safety practitioners in May 2015 to gain insight into which individual TMP strategies were used most frequently and which TMP strategies DOT staff were most interested in investigating for further research. The survey also solicited information and perspectives regarding how highway agencies manage a variety of work zone challenges and their success in doing so.

The survey form that was distributed is attached as Appendix A. The survey was based on the FHWA grouping of strategies—TO, TTC, and public information. The following outline shows the strategies included in the survey:

A. **Part A** related to TO strategies and TTC strategies. TO and TTC strategies are further subdivided into various categories:
    - Demand management strategies (9 individual strategies)
    - Corridor/network management strategies (7 individual strategies)
    - Work zone safety management strategies (9 individual strategies)
    - Traffic/incident management and enforcement strategies (14 individual strategies)
    - Control strategies (6 individual strategies)
    - Traffic control devices (descriptive questions)
    - Intermodal Control Strategies (descriptive questions)

B. **Part B** related to the Public Information strategies, which were subdivided into the following:
    - Public awareness strategies (6 individual strategies)
    - Motorist information strategies (10 individual strategies)

C. **Part C** related to Project Coordination and Innovative Construction Strategies.

Under each subject area groupings, practitioners were first asked to indicate their agency's experience using a rating system based on frequency of use, applicable roadways, effectiveness, and public feedback response. Respondents were requested to provide two example projects where individual strategies have been used. Respondents were also asked to indicate if their agency conducted any research, field trials, *before-after* studies, etc., on individual strategies.

After ranking the individual strategies, the respondents were next asked to choose two strategies for further investigation. Respondents could also add other factors of interest using free response text boxes. The electronic survey also provided an option to upload documents.

The practitioner survey responses are voluminous and therefore are provided as a separate standalone document.

3.2. Results

Thirty-nine (39) states completed the survey. The results of each category of strategies are discussed below.

3.2.1 Demand Management Strategies

The survey results indicated that:

- Demand management strategies are not frequently used. Many states have indicated that their traffic volumes and delays are not high enough to warrant using demand management strategies.
- Transit service improvements were used on a limited basis by 38 percent of respondents, mainly on arterial roadways, and was considered to be highly effective by almost 29 percent. Public response was cited as satisfactory by 15.4 percent of respondents.
- Shuttle services were used by 61 percent of respondents on a limited basis, mainly on arterial roadways (59 percent), and was considered highly effective by 20 percent. Public response was cited as satisfactory by 13 percent of respondents.

Respondents were also asked to identify their choice of demand management strategies that they were interested in learning more about or for further research/investigation. The highest rated strategies were:

- Park-and-ride promotion (14 percent).
- Shuttle services (11 percent).

3.2.2 Corridor/Network Management Strategies

The survey results indicated that:

- Corridor/network management strategies are not frequently used. Many states have indicated that their traffic volumes and delays are not high enough to warrant use of corridor/network management strategies.
- Sixty-two percent of respondents indicated they used street/intersection improvements on a limited basis. Fifty percent indicated using this strategy on arterial roadways and 42 percent considered them highly effective. Public response was cited as very good by 16 percent of the respondents.

- Fifty-nine percent of respondents indicated using truck/heavy vehicle restrictions on a limited basis. Sixty-four percent indicated using this strategy on both interstates/freeways and arterial roadways, and 52 percent considered this strategy moderately effective. Public response was cited as satisfactory by 16 percent of respondents.

Respondents were also asked to identify their choice of corridor/network management strategies that they were interested in learning more about or for further research/investigation. The highest rated strategies were:

- Dynamic lane closure system (36 percent of respondents).
- Truck lane restrictions (20 percent of respondents).

( ) refers to percent of respondents.

3.2.3 Work Zone Safety Management Strategies

The survey results indicated:

- Frequently used work zone safety management strategies are:
  - Speed limit reduction (73 percent)—83 percent indicated using this strategy on both interstates/freeways and arterial roadways and 57 percent considered this strategy moderately effective.
  - Positive protection (84 percent)—86 percent indicated using this strategy on both interstates/freeways and arterial roadways and 84 percent considered this strategy highly effective.
- Work zone safety management strategies used on a limited basis are:
  - Temporary rumble strips (61 percent)—50 percent indicated using this strategy on arterial/local roadways and 36 percent considered this strategy moderately effective.
  - Movable traffic barrier (49 percent)—68 percent indicated using this strategy on interstates/freeways and 70 percent considered this strategy highly effective.
  - Automated Flagger Assistance Devices (AFAD) (43 percent)—100 percent indicated using this strategy on arterial/local roadways and 47 percent considered this strategy moderately effective.

Respondents were also asked to identify their choice of work zone safety management strategies that they were interested in learning more about or for further research/investigation. The highest rated strategies were:

- Temporary Rumble Strips (18 percent).
- Variable Speed Limits (18 percent).

3.2.4 Traffic/Incident Management and Enforcement Strategies

The survey results indicated that:

- Most frequently used traffic/incident management and enforcement strategy is increased penalties for work zone violations (85 percent). About 87 percent indicated using this strategy on both interstates/freeways and arterial roadways and 48 percent considered this strategy moderately effective.
- Traffic/incident management and enforcement strategies used on a limited basis are:
    - ITS for traffic monitoring/management (53 percent)—60 percent indicated using this strategy on interstates/freeways and 52 percent considered this strategy moderately effective.
    - ITS for detouring traffic (56 percent)—65 percent indicated using this strategy on interstates/freeways and 43 percent considered this strategy moderately effective.
    - Tow/freeway service patrol (53 percent)—92 percent indicated using this strategy on interstates/freeways and 58 percent considered this strategy highly effective.
    - Paid police enforcement (48 percent)—55 percent indicated using this strategy on both interstates/freeways and arterial roadways and 50 percent considered this strategy highly effective.
    - Surveillance (Closed-Circuit Television [CCTV, loop detectors, lasers, probe vehicles]) (42 percent)—55 percent indicated using this strategy on interstates/freeways and 40 percent considered this strategy moderately effective.

Respondents were also asked to identify their choice of traffic/incident management and enforcement strategies that they were interested in learning more about or for further research/investigation. The highest rated strategies were:

- ITS for traffic monitoring/management (19 percent).
- Queue Warning System (19 percent).
- Automated Enforcement (17 percent).

3.2.5 Control Strategies

The literature review showed several case studies, most of them relating to accelerated bridge construction techniques, where agencies used control strategies. However, no evaluations were found. The survey results indicated that:

- Frequently used control strategies are:
    - Night Work (84 percent)—83 percent indicated using this strategy on both interstates/freeways and arterial roadways and 44 percent considered this strategy highly effective.

- Weekend Work (57 percent)—81 percent indicated using this strategy on both interstates/freeways and arterial roadways and 42 percent considered this strategy highly effective.
- Two-way traffic on one side of a divided facility (crossover) (51 percent)—51 percent indicated using this strategy on both interstates/freeways and arterial roadways and 52 percent considered this strategy highly effective.

- Control strategies used on a limited basis were:
  - Full Roadway Closures (73 percent)—58 percent indicated using this strategy on both interstates/freeways and arterial roadways and 72 percent considered this strategy highly effective.
  - Offsite detours/use of alternative routes (62 percent)—69 percent indicated using this strategy on both interstates/freeways and arterial roadways and 48 percent considered this strategy moderately effective.

Respondents were also asked to identify their choice of control strategies that they were interested in learning more about or for further research/investigation. The highest rated strategies were:

- Night Work (24 percent).
- Full Roadway Closure (21 percent).
- Reversible Lanes (21 percent).

3.2.6 Traffic Control Devices

None of the respondents indicated conducting research or an interest in evaluating new traffic control devices, revisions to the application or manner of use of an existing traffic control device, or a provision not specifically described in the Manual on Uniform Traffic Control Devices (MUTCD) (e.g., colored temporary pavement markings, alternative signs, and colored drums).

3.2.7 Public Awareness Strategies

The literature review showed several examples of using Public Awareness Strategies. No evaluations were found relating to the effectiveness of individual public awareness strategies.

The survey results indicated that:

- Most frequently used public awareness strategy is Social media (Twitter, Facebook, etc.) (59 percent). About 81 percent indicated using this strategy on both interstates/freeways and arterial roadways and 58 percent considered this strategy moderately effective.
- Public awareness strategies used on a limited basis are:

- — Project Website (55 percent)—75 percent indicated using this strategy on both interstates/freeways and arterial roadways and 57 percent considered this strategy highly effective.
- — Community task forces (39 percent)—46 percent indicated using this strategy on both interstates/freeways and arterial roadways and 43 percent considered this strategy moderately effective.
- — Real-time video display of project road/s information on Website (34 percent)—61 percent indicated using this strategy on both interstates/freeways and arterial roadways and 33 percent considered this strategy moderately effective.

Respondents were also asked to identify their choice of public awareness strategies that they were interested in learning more about or for further research/investigation. The highest rated strategies were:

- Social media (Twitter, Facebook, etc.) (27 percent).
- Real-time video display of project road/s information on Website (21 percent).
- Project Website (15 percent).

3.2.8 Motorist Information Strategies

Changeable message signs (CMSs) and dynamic speed message signs are two of the most widely evaluated TMP strategies followed by temporary motorist information signs and CB Wizard Alert system. The only evaluation found of Highway advisory radio (HAR) was from 1981. No evaluations were found of the remaining motorist information strategies (traffic radio, extinguishable signs, highway information network, 511 systems, and TMC).

The survey results indicated that:

- Frequently used motorist information strategies are:
  - — CMS (91 percent)—94 percent indicated using this strategy on both interstates/freeways and arterial roadways and 48 percent considered this strategy moderately effective.
  - — 511 travel information (wireless, handheld, in vehicle) (50 percent)—78 percent indicated using this strategy on both interstates/freeways and arterial roadways.
  - — Temporary motorist information signs (42 percent)—83 percent indicated using this strategy on both interstates/freeways and arterial roadways and 71 percent considered this strategy moderately effective.
- Public awareness strategies used on a limited basis were:
  - — Dynamic speed message sign (44 percent)—52 percent indicated using this strategy on both interstates/freeways and arterial roadways and 62 percent considered this strategy moderately effective.

  - — HAR (41 percent)—75 percent indicated using this strategy on interstates/freeways and 31 percent considered this strategy effective.
  - — Highway information network (Web-based) (39 percent)—72 percent indicated using this strategy on both interstates/freeways and arterial roadways and 43 percent considered this strategy moderately effective.

Respondents were also asked to identify their choice of motorist information strategies that they were interested in learning more about or for further research/investigation. The highest rated strategies were:

- Dynamic speed message sign (20 percent).
- Freight travel information (20 percent).

3.2.9 Project Coordination and Innovative Construction Strategies

The survey indicated that states use innovative construction strategies to accelerate project completion. However, respondents did not provide sufficient information on the advantages, selection factors, and price and time reduction information to draw specific conclusions. General conclusions are as follows:

- Legal issues remain a barrier to implementation, especially with design–build contracting methods.
- Agencies use very few systematic selection processes to guide the implementation.
- Very few agencies perform a systematic analysis of the benefits derived from using contracting methods.

4.0 Selection of Treatments for Field Evaluations

The list of treatments for field evaluations were identified based on a combination of past research, state survey responses, and input from panel members. This section discusses the initial and final methodology used to select the treatments for field evaluations.

4.1. Initial List of Treatments

The FHWA has identified approximately 100 work zone strategies that represent the three main TMP areas—TTC, public information, and TO. It would be ideal to conduct evaluations and/or case studies of all work zone strategies, but of course, this is not practical for any one project.

To narrow the strategies for possible field evaluations, it was first necessary to eliminate strategies that had already proved effective or for which a general evaluation is not possible. Several strategies fall within these groups as listed below:

- Strategies that are mandated by the 2009 MUTCD or state laws (traffic control devices).
- Strategies that are already proven effective or where a wealth of information is currently available (e.g. dynamic speed message signs, portable message signs, night work).
- Strategies that cannot be quantitatively evaluated to document the effect on safety or mobility (e.g. social media, project website, real-time video display, freight travel information).
- Strategies that are highly specific to a particular location (or specific to the system deployed) and are therefore non-transferrable (e.g. park-and-ride promotion, shuttle services, ITS for traffic monitoring).
- Strategies that are dependent on the legislature in that particular state/agency (e.g. automated enforcement, warning lights).
- Strategies whose use in work zones could not be found (e.g. High-occupancy vehicle [HOV] lanes, toll/congestion pricing).

As noted above, the team focused on a smaller subset of strategies as possible options for field evaluations. This smaller subset was then combined with practitioner survey input and available literature to identify potential treatments for field evaluation. Table 2 highlights the strategies that were explicitly considered. The effectiveness of past research is broken down into high, medium, and low. High previous research indicates more than five past studies, medium is between three and five, and low indicates a single study or none at all.

Of the top 27 strategies identified in Table 2, the team determined that 12 strategies were already sufficiently addressed in the literature. The items eliminated from further consideration for Phase II are marked as high previous research in Table 2.

Other strategies were found to have research gaps, but study design considerations make it infeasible to assess those strategies effectively as part of this effort. These include:

- Literature/instances of the use of HOV lanes and toll/congestion pricing under work zone conditions is nonexistent.
- Temporary traffic signals for lane merge control on highways is a theoretical concept and requires considerable research prior to their real-world application.
- Although the intrusion alarms system can ideally alert workers when any vehicle intrudes into their work zone, the problems with these systems are evident and numerous. The workers and/or flaggers are unlikely to be able to hear an audible warning over the noise. Also, at issue was the number of times a system could be unnecessarily activated (false positive). Such false positives have the potential to cause workers to ignore the system altogether, thus negating the point of having it as a warning system. Another shortcoming is that some systems use a single detector upstream from the work zone and, thus, it is possible for vehicles to enter the work zone without activating the detector (a false negative). Furthermore, the heat and noise level produced by work zone equipment and vehicles passing by have been shown to interfere with infrared and ultrasonic detectors, again, also causing false positives. The few states that have experimented with intrusion alarms have all reported unreliable performance.
- Using automated enforcement in work zones requires state legislation. Currently, only a few states implement ASE programs in work zones and evidence of the program's effectiveness is widely available.

4.2. Initial List of Treatments Identified for Field Evaluation

Based on the above criteria, the team presented the following seven strategies as possible options for field evaluations. The strategies are listed below (in no particular order):

- Dynamic Lane Merge System.
- Ramp Metering.
- Reversible Lanes.
- Truck Lane Restrictions.
- Variable Speed Limits (VSL).
- Temporary Rumble Strips.
- Sequential Warning lights.
- Queue Warning System.

Table 2. Summary of Strategies Considered for Field Evaluation.

Strategy Area	Strategy Type	Previous Research[1]			Survey Recommended	Final Team Recommendation
		High	Medium	Low		
Transportation Demand Management (TDM)	1. Transit service improvements	X				
	2. Transit incentives	X				
	3. Shuttle services	X			X	
	4. Ridesharing/carpooling incentives	X				
	5. Park-and-ride promotion	X			X	
	6. HOV lanes			X		
	7. Toll/congestion pricing			X		
Corridor/ Network Management Strategies	***8. Dynamic lane closure system***		***X***		***X***	✓
	9. Ramp metering			***X***		✓
	10. Temporary traffic signals			X		
	11. Truck lane restrictions			X	X	✓
	12. Reversible lanes		***X***		***X***	✓
Work Zone Safety Management Strategies	13. Speed limit reduction	X				
	14. VSL			***X***	***X***	✓
	15. Movable traffic barrier systems		X			
	16. Temporary rumble strips			***X***	***X***	✓
	17. Intrusion alarms			X		
	18. Sequential warning lights			***X***		✓
	19. Automated Flagger Assistance Devices (AFADs)	X				
Motorist Information Strategies	20. Portable changeable message signs (PCMS)	X				
	21. Dynamic speed message sign	X			X	
	22. CB Wizard Alert System		X		X	
Traffic/ incident management and enforcement strategies	23. ITS for traffic monitoring/management	X			X	
	24. Cooperative/paid police enforcement	X				
	25. Automated enforcement		X		X	
	26. Increased penalties for violations	X				
	27. Queue Warning System		***X***		***X***	✓

[1] High indicates the presence of more than five past studies, medium is between three and five, and low indicates a single study or none at all.

4.3. Panel Comments on Initial List

From the team's suggested list, the Panel unanimously agreed to remove the following strategies.

- VSL: FHWA, as part of Accelerated Innovation Deployment grant, awarded $750,000 to Utah Department of Transportation to test, evaluate, and develop guidelines for the use of VSL in work zones. As a result of this new information, the Panel felt the inclusion of VSL for additional field studies is not the best use of the project resources and agreed to remove it from consideration for field evaluation.
- Queue Warning Systems and Dynamic Lane Merge Systems: several states were already implementing and evaluating these strategies.
- Sequential warning lights are inexpensive and the Panel considered the needs of the project would be better suited by focusing on other strategies.
- Temporary rumble strips are used extensively and several states are currently testing them.

4.4. Final List of Treatments for Field Evaluation

The Panel then agreed to evaluate the following strategies that are generally applicable to all DOTs, pending (1) acquisition of evaluation sites and (2) new information (evaluations) available that may eliminate any of these from consideration.

1. Truck Lane Restrictions.
2. Ramp Metering.
3. Reversible Lanes.

5.0 Field Evaluation of Truck Lane Restrictions

A large volume of trucks can degrade the speed, comfort, and convenience of passenger car drivers sharing the road. This problem is exacerbated in work zones that may operate at a reduced capacity or reduced operating speeds resulting from lane closures, lane-width reductions, geometrics, etc. One common approach is to impose certain restrictions on truck movements as a means of improving safety and mobility to reducing the effects of truck traffic on freeways. This is typically achieved through the use of standalone static signs (TRUCKS USE LEFT/RIGHT LANE) or in combination with PCMS.

The few studies that have attempted to determine the effects of truck restrictions on highway operations and safety have shown inconclusive results. Truck lane restrictions have not been evaluated in work zones. The goal of this study is to evaluate the operational and safety effectiveness of restricting trucks in work zones to a particular lane(s).

5.1. Site Selection and Characteristics

Through outreach efforts to state transportation agencies, the team identified the following three locations in Michigan as test sites for evaluation:

- SB I-75 from Dixie Highway to Swan Creek Road, Monroe County.
- SB US-23 Flex Route project between M-14 and Silver Lake Road, Washtenaw and Livingston Counties.
- NB US-23 Flex Route project between M-14 and Silver Lake Road, Washtenaw and Livingston Counties.

5.1.1 I-75, Monroe County, Michigan

This project included reconstruction of 5.6 mi of Interstate-75 from Dixie Highway to I-275 along with the rehabilitation of three bridges, replacement of another three bridges, and reconstruction of 10 ramps. I-75 runs north-south with three lanes in each direction.

Construction took place during two summer seasons—2015 (for the northbound roadbed) and 2016 (for the southbound roadbed). Truck lane restrictions were in place during the reconstruction of the southbound bed (April 1–September 30, 2016) to prevent trucks traveling on the patched shoulders and existing drain grates. Trucks were restricted to the left lane.

When truck lane restrictions were in place, SB I-75 had two 11-ft-wide lanes. The work zone speed limit was 60 mph. Trucks made up 30% of the traffic composition.

Truck lane restrictions were enforced through the use of static signs and a PCMS. The PCMS was placed in the median approximately 3 miles before the beginning of the taper. The first static sign was placed ½-mi upstream from the beginning of the taper, second static sign was placed 2 mi downstream of the taper, and the last static sign was placed a further 2 mi downstream of the second static sign. The message on the static signs and the PCMS was the same (TRUCKS USE LEFT LANE) (Figure 2).

Figure 2. Work zone truck lane restriction.

5.1.2 US-23, Washtenaw and Livingston Counties, Michigan

The project corridor is a 10-mi section of US-23 within Livingston and Washtenaw Counties. US-23 freeway is a major north-south arterial that traverses through the cities of Ann Arbor and Brighton. Every day, 60,000 to 65,000 vehicles on average travel US-23 between the US-23/M-14 interchange and Silver Lake Road. Congestion and delays are common, especially in the southbound direction during the morning peak period and in the northbound direction during the evening peak period. To lessen the effects of heavy directional commuter travel patterns and to promote safety, Michigan Department of Transportation (MDOT) had made several improvements to the corridor—replacing and repairing bridges, upgrading acceleration and deceleration ramps, upgrading pavement and medians, and installing a Flex Route system to manage peak hour traffic congestion. The Flex Route system is a lane-control system that uses cameras and electronic message boards to let drivers know when additional lanes are available for use during morning and afternoon peak travel periods. US-23 had two 11-ft-wide lanes in each direction. The work zone speed limit was 60 mph. Construction started in November 2016 and lasted until July 2018.

In spring 2017, when traffic was shifted to the outside (right) shoulder, the shoulder began to fail. MDOT repaired the areas that failed initially and started using static signs and PCMS to enforce truck lane restrictions to the left lane and keep trucks off the shoulders that were not repaired. Trucks were restricted to using the left lane in both the northbound and southbound directions. The project was not set up originally for trucks to use only the left lane.

5.2. Study Methodology

5.2.1 Data Collection Duration

I-75, Monroe County, Michigan. The agency conducted the *before* data collection March 29–30, 2016. The truck restriction was implemented March 31, 2016, and the *after* data were collected May 16–18, 2016.

US-23, Washtenaw and Livingston Counties, Michigan. The Agency collected data *with* the truck lane restrictions May 22–26, 2017, and *without* the truck lane restrictions from May 1-3, 2018. The truck lane restrictions were in place in both the northbound and southbound directions. Data were collected and evaluated for both directions.

5.2.2 Data Collection Procedures

Vehicular data were collected using Hi-Metrics Nu-Star in-pavement sensors. These nonintrusive sensors use vehicle magnetic-imaging technology to record vehicle data, thus reducing the possibility of drivers adjusting their speeds because of visible equipment and human observers. The dimensions of the sensors are 6.5 in. by 5.5 in. with a thickness of 0.625 in. Each sensor is placed in the center of the travel lane and as a vehicle passes over it, the sensor captures changes in the magnetic field. All vehicular data were collected by direction and by lane. The sensors measured the volume, speed, vehicle classification, headway, and gap data per lane.

The agency also screened all raw data to exclude missing data values and outliers, such as vehicles traveling at very low or very high speeds. Data were analyzed separately for passenger cars and commercial vehicles.

5.2.3 Measures of Effectiveness

The following operational MOEs were evaluated:

- **Compliance with truck restriction signing (measured as percentage of truck occupancy by lane)**. This is a measure of compliance with the restriction and shows whether the restrictions created a tangible reduction in the number of trucks in the left lane.
- **Mean speeds in the restricted and non-restricted lanes.** The expectation is that the redistribution of trucks into specific lanes will increase the speed in the restricted lane(s) and decrease the speed in the non-restricted lane(s) where trucks are forced to move and become more concentrated. Because the restrictions were intended to reduce the number of slow-moving trucks in the right lane, the right lane should exhibit increases in average speed.

- **Frequency of headway.** Vehicle headway is a measure of the temporal space between two vehicles, and is defined as the elapsed time between the arrival of the leading vehicle and the following vehicle at a designated test point. It is usually measured in seconds. Since the average of vehicle headways is the reciprocal of flow rate, vehicle headways represent microscopic measures of flows passing a point. To some extent, the minimum acceptable mean headway determines the roadway capacity. The agency used the K-S test, a goodness-of-fit test, to test whether there is a meaningful difference between the measured frequency distribution between the *before*-and-*after* conditions. This is a surrogate measure for safety.

- **Headway led by truck.** This MOE examines the number of instances where a vehicle leads a platoon of traffic. A platoon is defined as a vehicle traveling with a headway greater than 3 seconds, followed by one or more vehicles with a headway less than 3 seconds. As noted above, this MOE is also a surrogate measure for safety.

5.2.4 Method for a Statistical Test for the Lane Distribution of Trucks

To determine the proportion of vehicles complying with the truck lane restrictions between any of the data collection periods, a *z*-test for independent samples was computed. The null and alternative hypotheses for the test are:

- Null Hypothesis (H_0): There is no difference between the two-sample proportions, or H_0: $P_1 - P_2 = 0$
- Alternative Hypothesis (H_a): There is a difference between the two-sample proportions, H_0: $P_1 - P_2 \neq 0$.

Equation 1 shows the Z-statistic used to compute the statistical difference between the two proportions, where P_{SB} and P_{SA} are the sample proportions, n_1 and n_2 are sample sizes for the corresponding proportions being considered, and P is the combined proportion in both samples.

$$Z = \frac{P_{SB} - P_{SA}}{\sqrt{P(1-P)\left(\frac{1}{n_1} + \frac{1}{n_2}\right)}}$$

Equation 1. Z-statistic to determine the lane compliance between the before-after periods.

$$P = \frac{x_B + x_A}{n_B + n_A}$$

Equation 2. Combined proportion of vehicles during the *before*-after *data* collection periods.

P is calculated using Equation 2.
Where:

x_B, x_A = percentage of trucks for the *before*-and-*after* periods;
n_B, n_A = sample size in *before*-and-*after* periods.

The critical value when $\alpha = 0.05$ for a one-tail test is 1.96. The null hypothesis is rejected when the computed z-test exceeds the critical value, thus concluding that the difference in lane distribution of trucks being compared differ between the two collection periods being considered.

5.2.5 Method for a Statistical Test for the Truck Speeds

The comparison of the differences between truck speeds *before* and *after* the restriction was based on the *t*-test for independent samples. The *t*-statistic is commonly used to test the hypothesis of differences in population parameters. In this study, the null and alternative hypotheses for testing the differences in two population mean speed measures, μ_1 and μ_2, were:

- Null Hypothesis (H_0): There has not been a change in mean speeds as a result of truck lane restrictions, or H_0: $\mu_1 - \mu_2 = 0$.
- Alternative Hypothesis (H_a): There has been a decrease in mean speeds as a result of truck lane restrictions, or H_a: $\mu_1 - \mu_2 > 0$.

The agency calculated a *t*-statistic at each study site for each sensor location and between data collection periods. Independent two-sample *t*-statistics were applied to test for the difference between two sample means at each study site. Equation 3 shows the *t*-statistic for calculating large samples with known variables.

$$t = \frac{(\overline{X}_B - \overline{X}_A)}{\sqrt{\frac{s_B^2}{n_B} + \frac{s_A^2}{n_A}}}$$

Equation 3. *t*-statistic to test for the difference between two sample means.

Where:

$\overline{X}_B, \overline{X}_A$ = mean speed for the *before*-and-*after* periods;
s_B, s_A = standard deviation of speed for the *before*-and-*after* periods;
n_B, n_A = sample size in *before*-and-*after* periods.

The degrees of freedom (*df*) for the independent samples *t*-statistic is $n_A + n_B - 2$. The critical value when $\alpha = 0.05$ for a one-tail test is 1.645. The null hypothesis is rejected when the computed *t*-test exceeds the critical value, thus concluding that the mean speeds compared differ between the two collection periods being considered. An alternative method to determine the statistical significance of truck lane restrictions on mean speed is the *p*-value associated with the *t*-statistic. A low *p*-value (i.e., less than or equal to 0.05) indicates a high probability that implementing the truck lane restrictions influenced mean speeds between two data collection periods. The team computed *t*-statistic and *p*-values at each study site. It was anticipated that the difference in mean speeds at the control sites would not be statistically significant. However, if there is a statistically significant difference in mean speeds, the magnitude of this difference would need to be accounted for. In this case, the team added or subtracted, depending on whether it was positive or negative, to the numerator in Equation 1. As such, the mean speed difference computed at the treatment sites was adjusted to account for statistically significant mean speed differences at the treatment sites.

5.2.6 Method for a Statistical Test for Frequency of Headways

The comparison of the differences between vehicle headways with and without the ramp metering was based on the K-S test for independent samples. The K-S test is commonly used to obtain a probability of similarity between two distributions to determine whether two datasets differ significantly. The K-S test is nonparametric and assumption-free, meaning that it has the advantage of making no assumption about the distribution of data. The purpose of this test is to obtain the cumulative distribution function of the two distributions that need to be compared. The K-S distance is a measure defined as the maximum value of the absolute difference between two cumulative distribution functions; it measures the largest absolute difference between two distribution functions for varying time.

The K-S distance is defined by:

$$\rho_K(X,Y) := ||F-G||_\infty = \sup_{t \subset \mathbb{R}} |P(X \leq t) - P(Y \leq t)| = \sup_t |F(t) - G(t)|$$

The supremum is the least upper bound of a set. Given a sample of observations x = (x1;…., xn), the empirical distribution function *Fn* is given by the following expression

$$F_n(t) = \frac{1}{n}\#\{x_i | x_i \leq t\}$$

Where #{…..} denotes the number of elements contained in the set {…..} and F_n defines a discrete probability distribution function on the real line. For large values of *n,* the empirical distribution converges to the theoretical one.

A smaller K-S statistic value indicates a better goodness-of-fit, and in a two-sample K-S test, the decision to reject the null hypothesis is based on comparing the p-value with the significance level α.

5.3. Comparison of Results for Truck Lane Distribution

The primary interest in evaluating the effectiveness of truck lane restrictions is the percentage changes of the lane distribution of trucks at the test sites. The *without* and *with* percentages of lane distribution of trucks are to be compared.

5.3.1 SB I-75 Location

Table 3 and Figures 3 through 5 show the lane distributions of trucks in percentages *without* and *with* the truck lane restrictions.

Once the truck lane restrictions were implemented, the percentage of trucks in the left lane increased for all time periods. The percentage of trucks in the left lane increased by 67.7% in the morning peak period (6–9 a.m.), by 84.2% in the mid-day period (10 a.m.–1 p.m.) and by 89.7% in the evening peak period (3–6 p.m.).

When the truck lane restrictions were implemented, the percentage of trucks in the right lane decreased for all time periods. The percentage of trucks in the left lane decreased by 74 percent in the morning peak period (6–9 a.m.), by 68.1 percent in the mid-day period (10 a.m.–1 p.m.) and by 73.9 percent in the evening peak period (3–6 p.m.).

Table 3. SB I-75 Differences in lane distribution *without* and *with* truck lane restrictions.

Time	Lane	Percentage of Trucks			
		Without Truck Restrictions	With Truck Restrictions	Percent Change (%)	Significant Change
Morning Peak Period (6–9 a.m.)	Left Lane	16.1	27.0	+67.7	Significant
	Right Lane	41.2	10.7	-74.0	Significant
Mid-day Period (10 a.m.–1 p.m.)	Left Lane	20.2	37.2	+84.2	Significant
	Right Lane	53.0	16.9	-68.1	Significant
Evening Peak Period (3–6 p.m.)	Left Lane	12.6	23.9	+89.7	Significant
	Right Lane	36.4	9.5	-73.9	Significant

The statistical test shows that the percentage of trucks in the left lane significantly increased during all time periods (a = 0.05).

Figure 3 shows the differences in the percentage of trucks using the right and the left lane in the *without* and *with* conditions during the morning peak period (6–9 a.m.) at the SB I-75 test site. During this period, the percentage of trucks using the left lane increased from 16.1 percent without truck lane restrictions to 27 percent with the truck lane restrictions, an increase of 67.7 percent. During the same time period, the percentage of trucks using the right lane decreased from 41.2 percent without truck lane restrictions to 10.7 percent with the truck lane restrictions, a decrease of 74 percent.

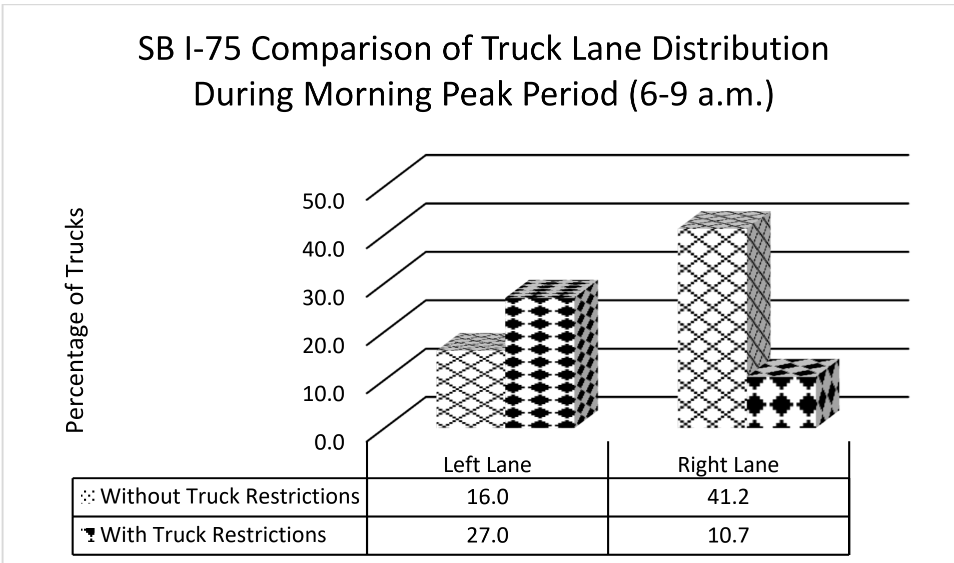


Figure 3. SB I-75 Comparison of truck lane distribution during morning peak period (6–9 a.m.).

Figure 4 shows the differences in the percentage of trucks using the right and the left lane in the *without* and *with* conditions during the mid-day period (10 a.m.–1 p.m.) at the SB I-75 test site. During this period, the percentage of trucks using the left lane increased from 20.2 percent without truck lane restrictions to 37.2 percent with the truck lane restrictions, an increase of 84.2 percent. During the same time period, the percentage of trucks using the right lane decreased from 53 percent without truck lane restrictions to 16.9 percent with the truck lane restrictions, a decrease of 68.1 percent.

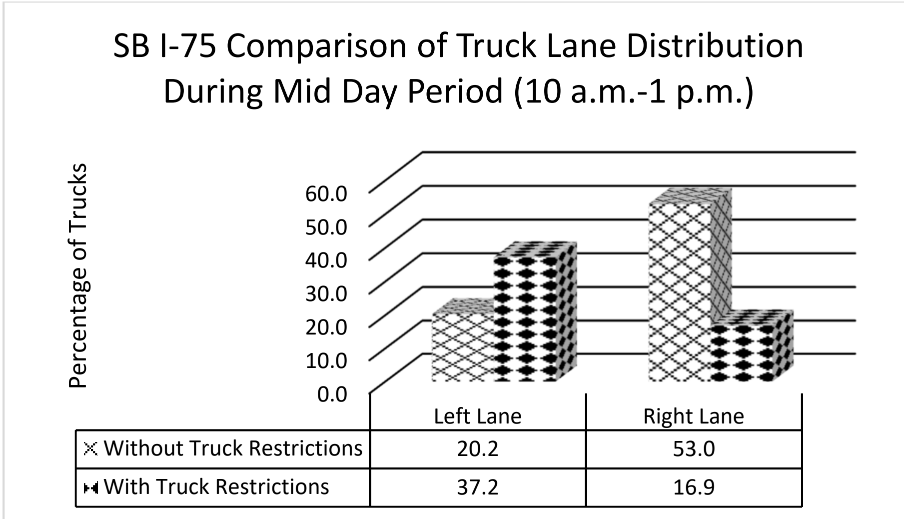


Figure 4. SB I-75 Comparison of truck lane distribution during mid-day period (10 a.m.–1 p.m.).

Figure 5 shows the differences in the percentage of trucks using the right and the left lane in the *without* and *with* conditions during the evening peak period (3–6 p.m.) at the SB I-75 test site During this period, the percentage of trucks using the left lane increased from 12.6 percent without truck lane restrictions to 23.9 percent with the truck lane restrictions, an increase of 89.7 percent. During the same time period, the percentage of trucks using the right lane decreased from 36.4 percent without truck lane restrictions to 9.5 percent with the truck lane restrictions, a decrease of 73.9 percent.

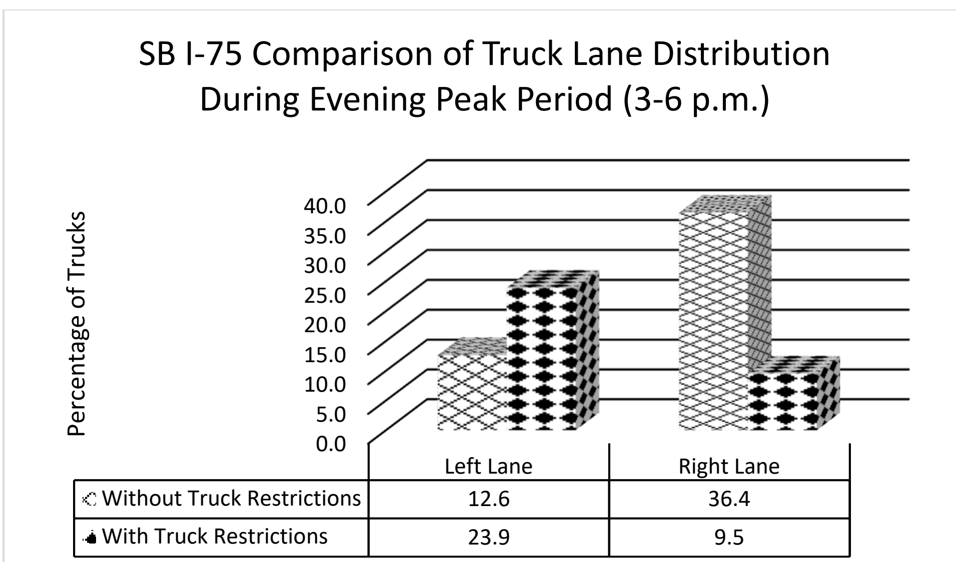


Figure 5. SB I-75 Comparison of truck lane distribution during evening peak period (3–6 p.m.).

5.3.2 SB US-23 Location

Table 4 and Figures 6 through 8 show the lane distributions of trucks in percentages *without* and *with* the truck lane restrictions.

When the truck lane restrictions were implemented, the percentage of trucks in the left lane increased for all time periods. The percentage of trucks in the left lane increased by 446.7% in the morning peak period (6–9 a.m.), by 465.6% in the mid-day period (10 a.m.–1 p.m.) and by 370.8% in the evening peak period (3–6 p.m.).

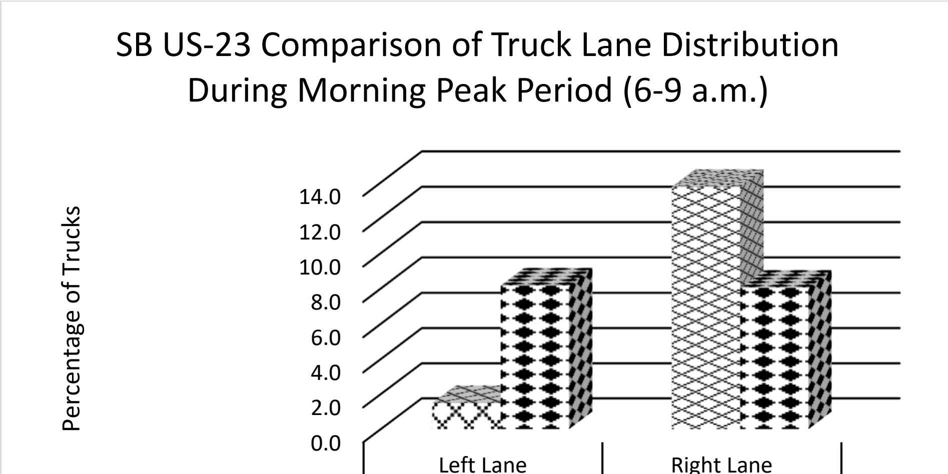
When the truck lane restrictions were implemented, the percentage of trucks in the right lane decreased for all time periods. The percentage of trucks in the right lane decreased by 41.6% in the morning peak period (6–9 a.m.), by 45.5% in the mid-day period (10 a.m.–1 p.m.) and by 51% in the evening peak period (3–6 p.m.).

The statistical test shows that the percentage of trucks in the left lane was significantly increased (a = 0.05) during the mid-day and evening peak periods.

Table 4. SB US-23 Differences in lane distribution *without* and *with* truck lane restrictions.

Time	Lane	Percentage of Trucks			
		Without Truck Restrictions	With Truck Restrictions	Percent Change (%)	Significant Difference?
Morning Peak Period (6–9 a.m.)	Left Lane	1.5	8.2	+446.7	Not Significant
	Right Lane	13.7	8.0	-41.6	Significant
Mid-Day Period (10 a.m.–1 p.m.)	Left Lane	3.2	18.1	+465.6	Significant
	Right Lane	21.1	11.5	-45.5	Significant
Evening Peak Period (3–6 p.m.)	Left Lane	2.4	11.3	+370.8	Significant
	Right Lane	15.1	7.4	-51.0	Significant

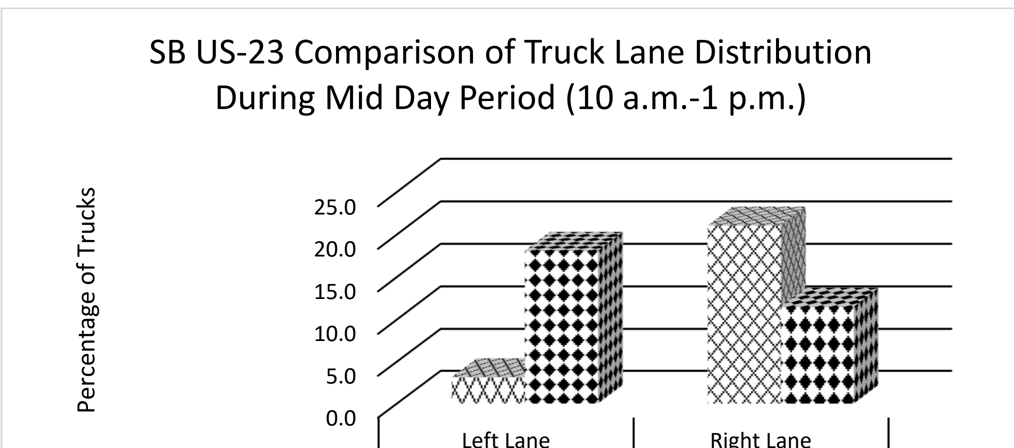
Figure 6 shows the differences in the percentage of trucks using the right and the left lane in the *without* and *with* conditions during the morning peak period (6–9 a.m.) at the SB US-23 test site. During this period, the percentage of trucks using the left lane increased from 1.5 percent without truck lane restrictions to 8.2 percent with the truck lane restrictions, an increase of 446.7 percent. During the same time period, the percentage of trucks using the right lane decreased from 13.7 percent without truck lane restrictions to 8 percent with the truck lane restrictions, a decrease of 41.6 percent.



	Left Lane	Right Lane
Without Truck Restrictions	1.5	13.7
With Truck Restrictions	8.2	8.0

Figure 6. SB US-23 comparison of truck lane distribution during morning peak period (6–9 a.m.).

Figure 7 shows the differences in the percentage of trucks using the right and the left lanes in the *without* and *with* conditions during the mid-day period (10 a.m.–1 p.m.) at the SB US-23 test site. During this period, the percentage of trucks using the left lane increased from 3.2 percent without truck lane restrictions to 18.1 percent with the truck lane restrictions, an increase of 465.6 percent. During the same time period, the percentage of trucks using the right lane decreased from 21.1 percent without truck lane restrictions to 11.5 percent with the truck lane restrictions, a decrease of 45.5 percent.



	Left Lane	Right Lane
Without Truck Restrictions	3.2	21.1
With Truck Restrictions	18.1	11.5

Figure 7. SB US-23 Comparison of truck lane distribution during mid-day period (10 a.m.–1 p.m.).

Figure 8 shows the differences in the percentage of trucks using the right and the left lane in the *without* and *with* conditions during the evening peak period (3–6 p.m.) at the SB US-23 test site. During this period, the percentage of trucks using the left lane increased from 2.4 percent without truck lane restrictions to 11.3 percent with the truck lane restrictions, an increase of 370.8 percent. During the same time period, the percentage of trucks using the right lane decreased from 15.1 percent without truck lane restrictions to 7.4 percent with the truck lane restrictions, a decrease of 51 percent.

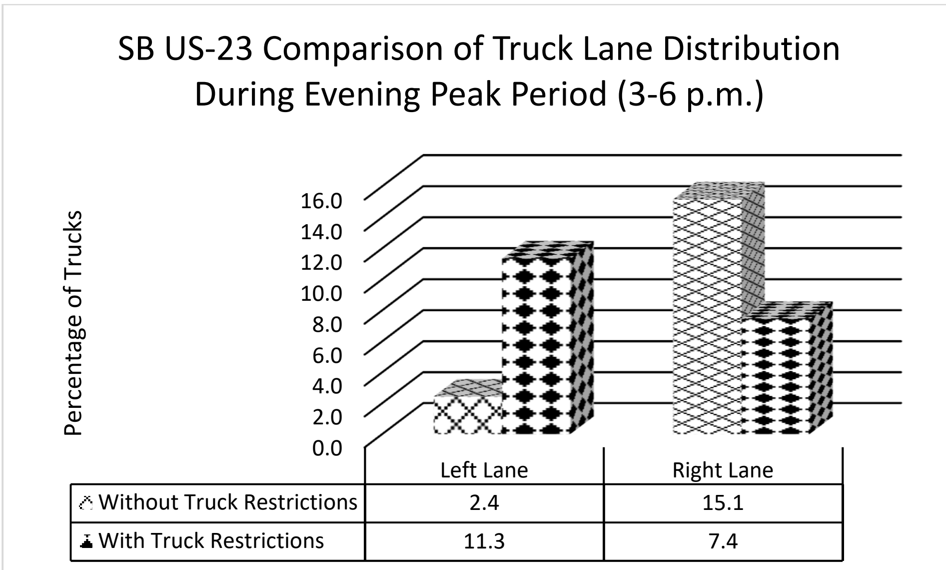


Figure 8. SB US-23 Comparison of truck lane distribution during evening peak period (3–6 p.m.).

5.3.3 NB US-23 Location

Table 5 and Figures 9 through 11 show the lane distributions of trucks in percentages *without* and *with* the truck lane restrictions.

When the truck lane restrictions were implemented, the percentage of trucks in the left lane increased for all time periods. The percentage of trucks in the left lane increased by 928% in the morning peak period (6–9 a.m.), by 726.9% in the mid-day period (10 a.m.–1 a.m.) and by 415.2% in the evening peak period (3–6 p.m.).

When the truck lane restrictions were implemented, the percentage of trucks in the right lane decreased for all time periods. The percentage of trucks in the right lane decreased by 59.9% in the morning peak period (6–9 a.m.), by 52.3% in the mid-day period (10 a.m.–1 p.m.) and by 54.7% in the evening peak period (3–6 p.m.).

The statistical test shows that the percentage of trucks in the left lane was significantly increased (a = 0.05) for all time periods.

Table 5. NB US-23 Differences in lane distribution without and with truck lane restrictions.

Time	Lane	Percentage of Trucks			
		Without Truck Restrictions	With Truck Restrictions	Percent Change (%)	Significant Difference?
Morning Peak Period (6–9 a.m.)	Left Lane	2.5	25.7	+928.0	Significant
	Right Lane	20.7	8.3	-59.9	Significant
Mid-day Period (10 a.m.–1 p.m.)	Left Lane	2.6	21.5	+726.9	Significant
	Right Lane	19.5	9.3	-52.3	Significant
Evening Peak Period (3–6 p.m.)	Left Lane	2.1	10.9	+415.2	Significant
	Right Lane	13.2	6.0	-54.7	Significant

Figure 9 shows the differences in the percentage of trucks using the right and the left lane in the 'without' and 'with' conditions during the morning peak period (6-9 a.m.) at the NB US-23 test site. During this period, the percentage of trucks using the left lane increased from 2.5 percent without truck lane restrictions to 25.7 percent with the truck lane restrictions, an increase of 928 percent. During the same time period, the percentage of trucks using the right lane decreased from 20.7 percent without truck lane restrictions to 8.3 percent with the truck lane restrictions, a decrease of 59.9 percent.

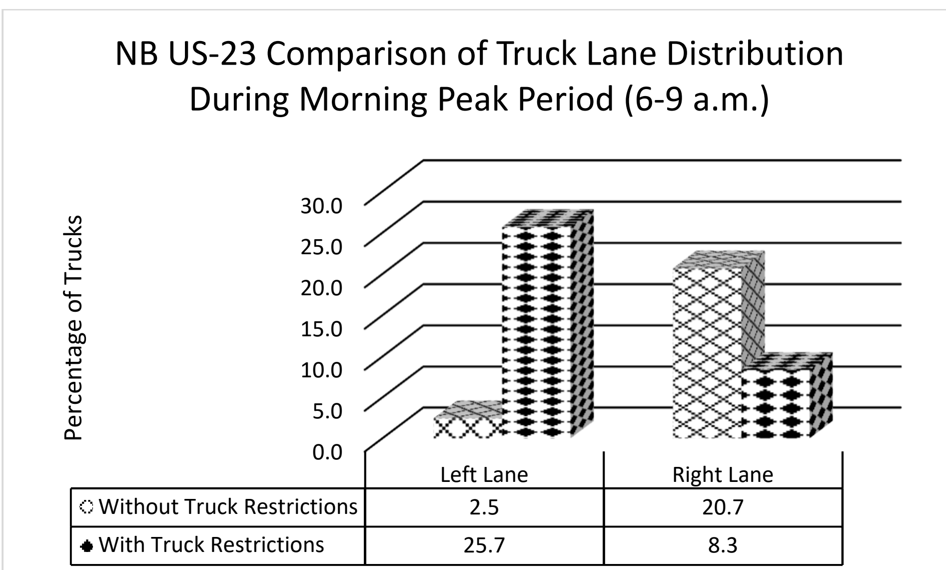


Figure 9. NB US-23 Comparison of truck lane distribution during morning peak period (6–9 a.m.).

Figure 10 shows the differences in the percentage of trucks using the right and the left lane in the *without* and *with* conditions during the mid-day period (10 a.m.–1 p.m.) at the NB US-23 test site. During this period, the percentage of trucks using the left lane increased from 2.6 percent without truck lane restrictions to 21.5 percent with the truck lane restrictions, an increase of 726.9 percent. During the same time period, the percentage of trucks using the right lane decreased from 19.5 percent without truck lane restrictions to 9.3 percent with the truck lane restrictions, a decrease of 52.3 percent.

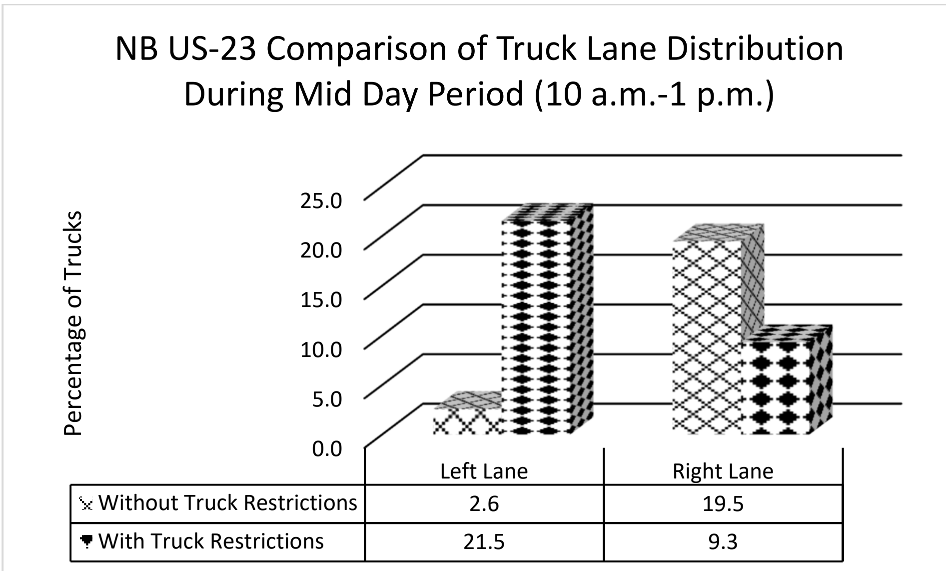


Figure 10. NB US-23 Comparison of truck lane distribution during mid-day period (10 a.m.–1 p.m.).

Figure 11 shows the differences in the percentage of trucks using the right and the left lane in the *without* and *with* conditions during the evening peak period (3–6 p.m.) at the NB US-23 test site. During this period, the percentage of trucks using the left lane increased from 2.1 percent without truck lane restrictions to 10.9 percent with the truck lane restrictions, an increase of 415.2 percent. During the same time period, the percentage of trucks using the right lane decreased from 13.2 percent without truck lane restrictions to 6 percent with the truck lane restrictions, a decrease of 54.7 percent.

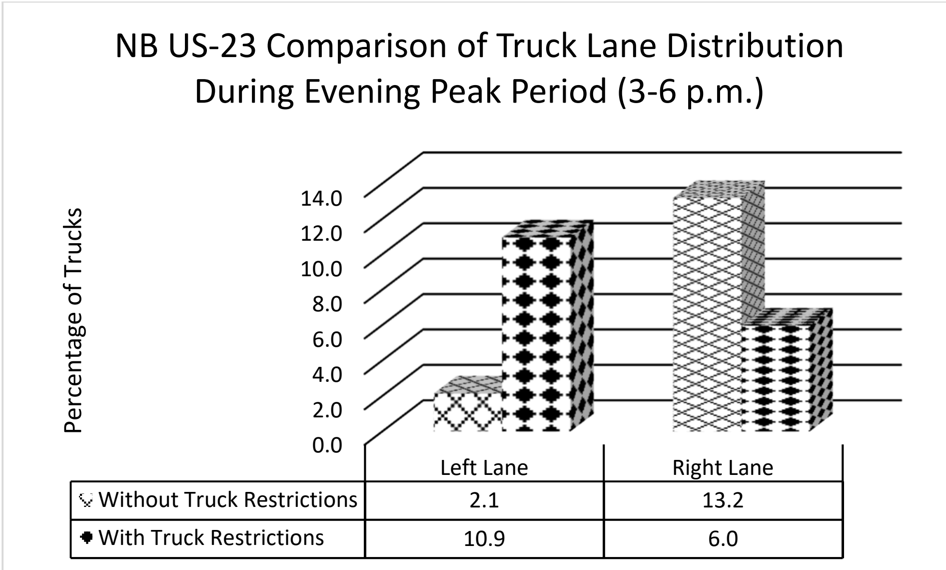


Figure 11. NB US-23 Comparison of truck lane distribution during evening peak period (3–6 p.m.).

5.3.4 Combined For All Sites

Table 6 shows the changes in lane distribution for all three sites for all time periods. At all three sites trucks were restricted to using the left lane and the data clearly show that the truck lane restrictions were effective in creating a tangible increase in the number of trucks using the left lane.

When the truck restrictions were in place, the percentage change in trucks using the left lane, for all time periods, increased by 84.76% for SB I-75, 502.64% for SB US-23, and 669.04% for NB US-23. For all sites combined, the percentage change in trucks using the left lane, for all time periods, increased by 234.96%.

When the truck restrictions were in place, the percentage change in trucks using the right lane, for all time periods, decreased by 71.74% for SB I-75, 48.31% for SB US-23, and 51.32 percent for NB US-23. For all sites combined, the percentage change in trucks using the right lane, for all time periods, decreased by 59.36%.

Table 6. Lane distribution differences without and with truck lane restrictions for all sites.

Lane	Location	Without Truck Restrictions			With Truck Restrictions			Percent Change (%)
		Car Volumes	Truck Volumes	% of Trucks	Car Volumes	Truck Volumes	% of Trucks	
Left Lane	SB I-75	22,232	4746	17.59	21,201	10209	32.50	84.76
	SB US-23	35,987	834	2.27	20,943	3318	13.68	502.64
	NB US-23	28,507	697	2.39	18,189	4096	18.38	669.04
	Totals	**86,726**	**6,277**	**6.75**	**60,333**	**17623**	**22.61**	**234.96**
Right Lane	SB I-75	9,465	7,691	44.83	18,128	2630	12.67	-71.74
	SB US-23	23,333	4,749	16.91	24,696	2366	8.74	-48.31
	NB US-23	2,1031	4436	17.42	26,899	2493	8.48	-51.32
	Totals	**53,829**	**16,876**	**23.87**	**69,723**	**7489**	**9.70**	**-59.36**

- SB I-75: Data were collected for 40 hours in the *without* condition and for 46 hours in the *with* condition.
- SB US-23 and NB US-23: Data were collected for 48 hours in the *without* condition and for 46 hours in the *with* condition.

5.4. Comparison of Results for Truck Speeds

A comparison of truck speeds was conducted to evaluate the effect of lane-use restriction. Besides the evaluation based on the lane distribution of trucks, a comparison of truck speeds can also determine if lane-use restrictions cause changes in travel characteristics. The truck speeds were compared separately according to the time period; morning peak period (6–9 a.m.), mid-day period (10 a.m.–1 p.m.), and evening peak period (3–6 p.m.) for each site.

5.4.1 SB I-75 Location

Table 7 shows the comparison of average speed of trucks *without* and *with* the truck lane restrictions.

With the truck restrictions in place, the average truck speeds reduced in the right lane during the morning peak period (by 16.39%) and mid-day period (by 16.03%) and evening peak period (by 16.25%). These reductions are expected because if truck lane restrictions are effective, it is assumed that the number of passenger cars in the right lane would increase and trucks would travel at the prevailing speed.

With the truck restrictions in place, the average truck speeds increased in the left lane during the morning peak period (by 9.38%), mid-day period (by 7.17%), and evening peak period (by 7.58%). These increases were are expected, as vehicles traveled close to the posted speed limit of 60 mph.

The changes in average speeds of trucks are all statistically significant ($\alpha = 0.05$).

Table 7. SB I-75 truck speeds *without* and *with* truck lane restrictions.

	Left Lane Average Speeds (mph)			Right Lane Average Speeds (mph)		
	6–9 a.m.	10 a.m.–1 p.m.	3–6 p.m.	6–9 a.m.	10 a.m.–1 p.m.	3–6 p.m.
Without Truck Restrictions	52.27	51.97	51.81	66.16	64.85	64.84
With Truck Restrictions	57.17	55.70	55.74	55.31	54.46	54.30
% Change	+9.38	+7.17	+7.58	-16.39	-16.03	-16.25
Significant Change	Yes	Yes	Yes	Yes	Yes	Yes

Table 8 shows the comparison of average speed of passenger cars *without* and *with* the truck lane restrictions.

With the truck restrictions in place, the passenger car average speeds reduced in the right lane during the morning peak period (by 15.04%), mid-day period (by 14.05%), and evening peak period (by 14.13%).

With the truck restrictions in place, the passenger car average speeds increased in the left lane during the morning peak period (by 8.82%), mid-day period (by 5.43%), and evening peak period (by 6.07%).

The changes in average speeds of passenger cars are all statistically significant ($\alpha = 0.05$).

Table 8. SB I-75 car speeds *without* and *with* truck lane restrictions.

	Left Lane Average Speeds (mph)			Right Lane Average Speeds (mph)		
	6–9 a.m.	10 a.m.–1 p.m.	3–6 p.m.	6–9 a.m.	10 a.m.–1 p.m.	3–6 p.m.
Without Truck Restrictions	58.02	56.03	56.97	70.89	68.27	68.60
With Truck Restrictions	63.14	59.07	60.42	60.23	58.68	58.91
% Change	+8.82	+5.43	+6.07	-15.04	-14.05	-14.13
Significant Change	Yes	Yes	Yes	Yes	Yes	Yes

5.4.2 SB US-23 Location

Table 9 shows the comparison of average speed of trucks *without* and *with* the truck lane restrictions.

With the truck restrictions in place, the average truck speeds reduced in the right lane during the morning peak period (by 4.19%), mid-day period (by 5.35%), and evening peak period (by 3.14%) as traffic volumes in the right lane increased.

With the truck restrictions in place, the average truck speeds increased in the left lane during the morning peak period (by 5.25%), decreased during the mid-day period (by 4.24%), and evening peak period (by 1.82%). It was observed that the truck speeds in the left lane in the *with* condition were somewhat higher than those in the *without* condition.

The changes in average speeds of trucks were all statistically significant ($\alpha = 0.05$), with the exception of the left lane during the evening peak period.

Table 9. SB US-23 truck speeds *without* and *with* truck lane restrictions.

	Left Lane Average Speeds (mph)			Right Lane Average Speeds (mph)		
	6–9 a.m.	10 a.m.–1 p.m.	3–6 p.m.	6–9 a.m.	10 a.m.–1 p.m.	3–6 p.m.
Without Truck Restrictions	60.65	64.46	64.10	57.52	58.83	57.87
With Truck Restrictions	63.83	61.72	62.94	55.11	55.68	56.05
% Change	5.25	-4.24	-1.82	-4.19	-5.35	-3.14
Significant Change	Yes	Yes	No	Yes	Yes	Yes

Table 10 shows the comparison of average speed of passenger cars *without* and *with* the truck lane restrictions.

With the truck restrictions in place, the passenger car average speeds increased slightly in the right lane during the morning peak period (by 1.11%), reduced during the mid-day period (by -2.66%), and evening peak period (by -1.07%).

With the truck restrictions in place, the passenger car average speeds increased slightly in the left lane during the morning peak period (by 1.55%), and decreased during the mid-day period (by 5.98%), and evening peak period (by 2.6%).

The changes in average speeds of passenger cars are all statistically significant ($\alpha = 0.05$).

Table 10. SB US-23 car speeds *without* and *with* truck lane restrictions.

	Left Lane Average Speeds (mph)			Right Lane Average Speeds (mph)		
	6–9 a.m.	10 a.m.–1 p.m.	3–6 p.m.	6–9 a.m.	10 a.m.–1 p.m.	3–6 p.m.
Without Truck Restrictions	64.10	69.38	68.10	60.32	63.40	62.38
With Truck Restrictions	65.09	65.23	66.33	60.99	61.71	61.71
% Change	1.55	-5.98	-2.60	1.11	-2.66	-1.07
Significant Change	Yes	Yes	Yes	Yes	Yes	Yes

5.4.3 NB US-23 Location

Table 11 shows the comparison of average speed of trucks *without* and *with* the truck lane restrictions.

With the truck restrictions in place, the average truck speeds increased significantly in the right lane during the morning peak period (by 23.53%), mid-day period (by 18.16%), and decreased during the evening peak period (by 16.26%).

With the truck restrictions in place, the average truck speeds decreased in the left lane during the morning peak period (by 14.65%), mid-day period (by 16.78%), and evening peak period (by 38.57%). It was observed that the truck speeds in left lane in the *without* condition were significantly lower than those in the right lane *without* condition.

The changes in average speeds of trucks are all statistically significant ($\alpha = 0.05$) with the exception of those in the left lane during the evening peak period.

Table 11. NB US-23 truck speeds *without* and *with* truck lane restrictions.

	Left Lane Average Speeds (mph)			Right Lane Average Speeds (mph)		
	6–9 a.m.	10 a.m.–1 p.m.	3–6 p.m.	6–9 a.m.	10 a.m.–1 p.m.	3–6 p.m.
Without Truck Restrictions	59.36	57.90	56.35	51.84	52.67	50.82
With Truck Restrictions	50.67	48.18	34.62	64.04	62.23	42.56
% Change	-14.65	-16.78	-38.57	23.53	18.16	-16.26
Significant Change	Yes	Yes	Yes	Yes	Yes	Yes

Table 12 shows the comparison of average speed of passenger cars *without* and *with* the truck lane restrictions.

With the truck restrictions in place, the passenger car average speeds increased significantly in the right lane during the morning peak period (by 17.7%), mid-day period (by 10.66%), and decreased during the evening peak period (by 33.14%).

With the truck restrictions in place, the passenger car average speeds decreased in the left lane during the morning peak period (by 12.85%), mid-day period (by 17.20%), and evening peak period (by 40.26%).

The changes in average speeds of passenger cars are all statistically significant ($\alpha = 0.05$).

Table 12. NB US-23 car speeds *without* and *with* truck lane restrictions.

	Left Lane Average Speeds (mph)			Right Lane Average Speeds (mph)		
	6–9 a.m.	10 a.m.–1 p.m.	3–6 p.m.	6–9 a.m.	10 a.m.–1 p.m.	3–6 p.m.
Without Truck Restrictions	60.58	59.79	58.33	56.61	56.29	54.38
With Truck Restrictions	52.80	49.51	34.84	66.63	62.30	36.36
% Change	-12.85	-17.20	-40.26	17.70	10.66	-33.14
Significant Change	Yes	Yes	Yes	Yes	Yes	Yes

5.5. Comparison of Headways Results

The vehicle headway is defined as the time (in seconds) or gap (in feet), between two successive vehicles as they pass a point on the roadway, measured from the same common feature of both vehicles. Headway is a good measure of congestion and lack of passing opportunities created by the traffic mix; it is also a good surrogate safety measure as lane changing and frequent passing generally lead to conflicts and the likelihood of crashes. In general, a longer headway accepted by a merging vehicle is safer than a shorter headway.

Car–truck interactions are viewed as the driving actions of non-truck drivers resulting from psychological discomfort in the vicinity of trucks, primarily due to truck physical/operational characteristics. While interactions can also arise from the truck driver perspective, they tend to be less significant behaviorally as cars are smaller in size and have better operational characteristics. There is a rich body of literature on safety issues involving trucks. These studies mostly focus on the analyses of crash data or on models to understand key causal factors in relation to crashes. However, the existing literature does not address the modeling of traffic flow interactions between trucks and other vehicles arising from a driver behavior perspective, especially those that do not lead to crashes. Such a capability is essential for analyzing strategies to mitigate car–truck interactions, which further influence traffic performance, safety, and the travel experience of non-truck drivers.

This study attempted to capture the effect of the car–truck interaction on vehicle headway, vehicle platoons and gap acceptance by different leading and following vehicle types.

5.5.1 Comparison of Results for Frequency of Headway

An evaluation of the headways accepted by the following vehicles in each lane was conducted to determine if there were any differences *without* and *with* the truck lane restrictions in place. An analysis of vehicle headways was conducted in the morning peak period (6–9 a.m.) and in the evening peak period (3–6 p.m.) to determine the average values and distribution during the *without* and *with* the truck lane restrictions.

5.5.1.1 SB I-75 Location

An analysis of headways of vehicles in the morning peak period (6–9 a.m.) was conducted to determine the average values and distribution for the *with* and *without* conditions. The K-S test was used to judge how faithfully a distribution fits the sample data. The K-S test was adopted to determine the goodness-of-fit in the work zone traffic condition.

Tables 13 and 14 summarize the K-S test results of *without* and *with* implementation of truck lane restrictions. The following describes the headway analysis comparison for the right lane and left lane.

SB I-75 Headway Analysis Results Using K-S Test—Left Lane

Figure 12 presents a visual performance comparison of headway distribution through cumulative distribution function in the morning peak period for *without* vs. *with* implementation of truck lane restriction on the left lane. The agency observed a slight shift in the headway distribution toward longer headway during the *with* condition. The *with* condition had a longer headway for approximately 50% of sample (cumulative percentage 20% to 70%) with a maximum headway difference of 50 ft. The median value of headway was 255 ft during the *without* condition as opposed to 286 ft during the *with* condition. With the significance level α of 0.05 and the sample size of 2,254 for the *without* condition and 2,730 for the *with* condition, the critical statistic of K-S test for the maximum difference between the cumulative distributions, D, was 0.04. The results of K-S test for the *without* condition vs. the *with* condition shows a value of D of 0.061 (greater than the critical value of 0.04), which suggests the differences in the two cumulative distributions are statistically significant.

Table 13. SB I-75 Headway analysis results using K-S test—left lane.

	Conditions	
	Without implementation of truck lane restrictions	With implementation of truck lane restrictions
Volume (Vehicle/3-hr)	2,254	2,370
Mean Headway (ft)	396	410
Median Headway (ft)	255	286
Maximum difference (D)	0.061	
Significance	Yes	

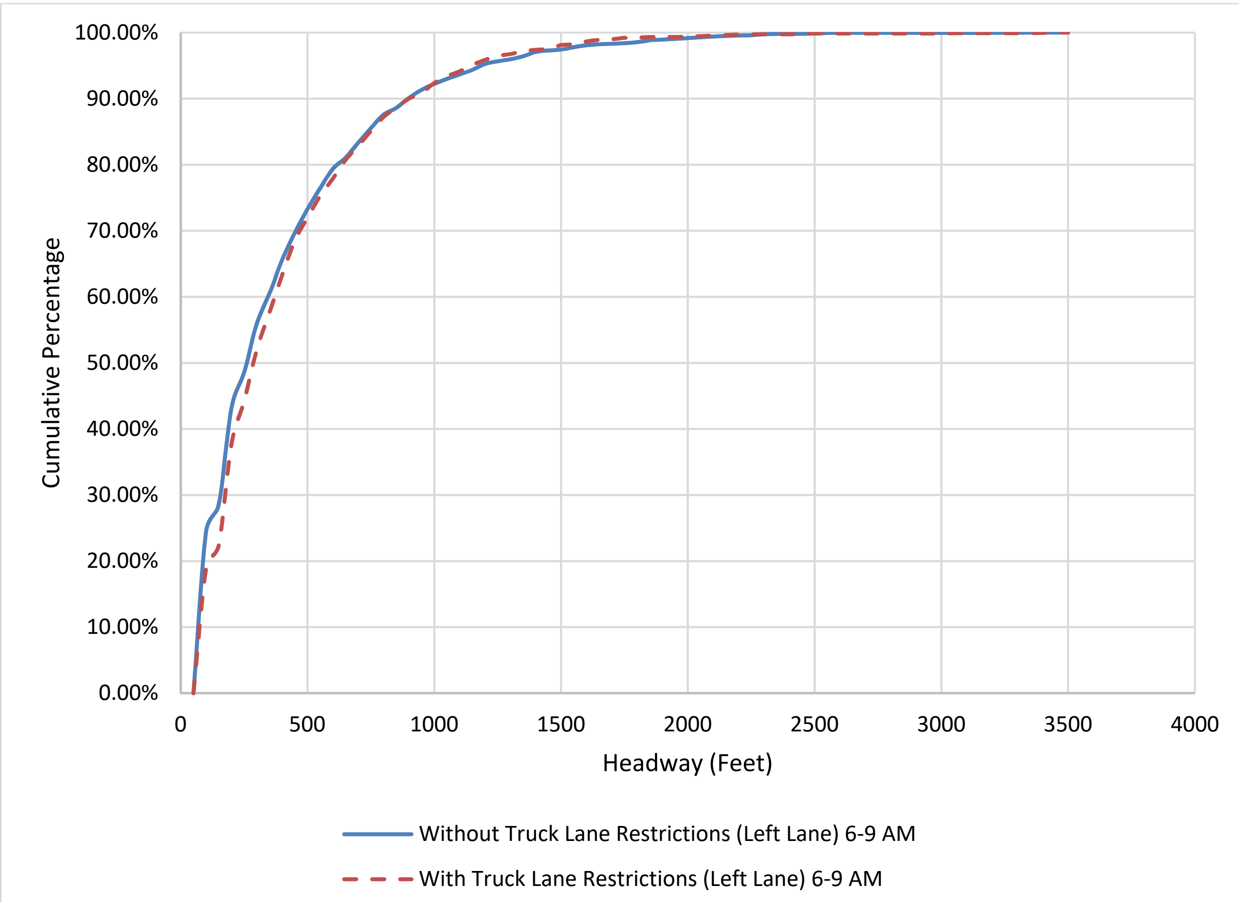


Figure 12. SB I-75 Cumulative headway distribution plot (left lane)—*without* vs. *with* condition (6–9 a.m.).

SB I-75 Headway Analysis Results Using K-S Test—Right Lane

Figure 13 presents a visual performance comparison of headway distribution through a cumulative distribution function in the morning peak period for the *without* condition vs. the *with* condition in the right lane. The agency observed a shift in the headway distribution toward longer headways during the *without* condition. The *without* condition had a longer headway in approximately 95% of the sample (cumulative percentage 5% to 100%) with a maximum headway difference of 400 ft. The median value of headway was 481 ft during the *without* condition as opposed to 367 ft during the *with* condition. With the significance level α of 0.05 and the sample size of 1,481 for the *without* condition and 1,679 for the *with* condition, the critical statistic of K-S test for the maximum difference between the cumulative distributions, D, was 0.05. The results of K-S test for the *without* condition vs. the *with* condition shows a value of D of 0.127 (greater than the critical value of 0.05), which suggests the differences in the two cumulative distributions are statistically significant.

Table 14. SB I-75 Headway analysis results using K-S test—right lane.

	Conditions	
	Without implementation of truck lane restrictions	**With implementation of truck lane restrictions**
Volume (Vehicle/3-hr)	**1,481**	**1,679**
Mean Headway (ft)	**732**	**556**
Median Headway (ft)	**481**	**367**
Maximum difference (D)	**0.127**	
Significance	**Yes**	

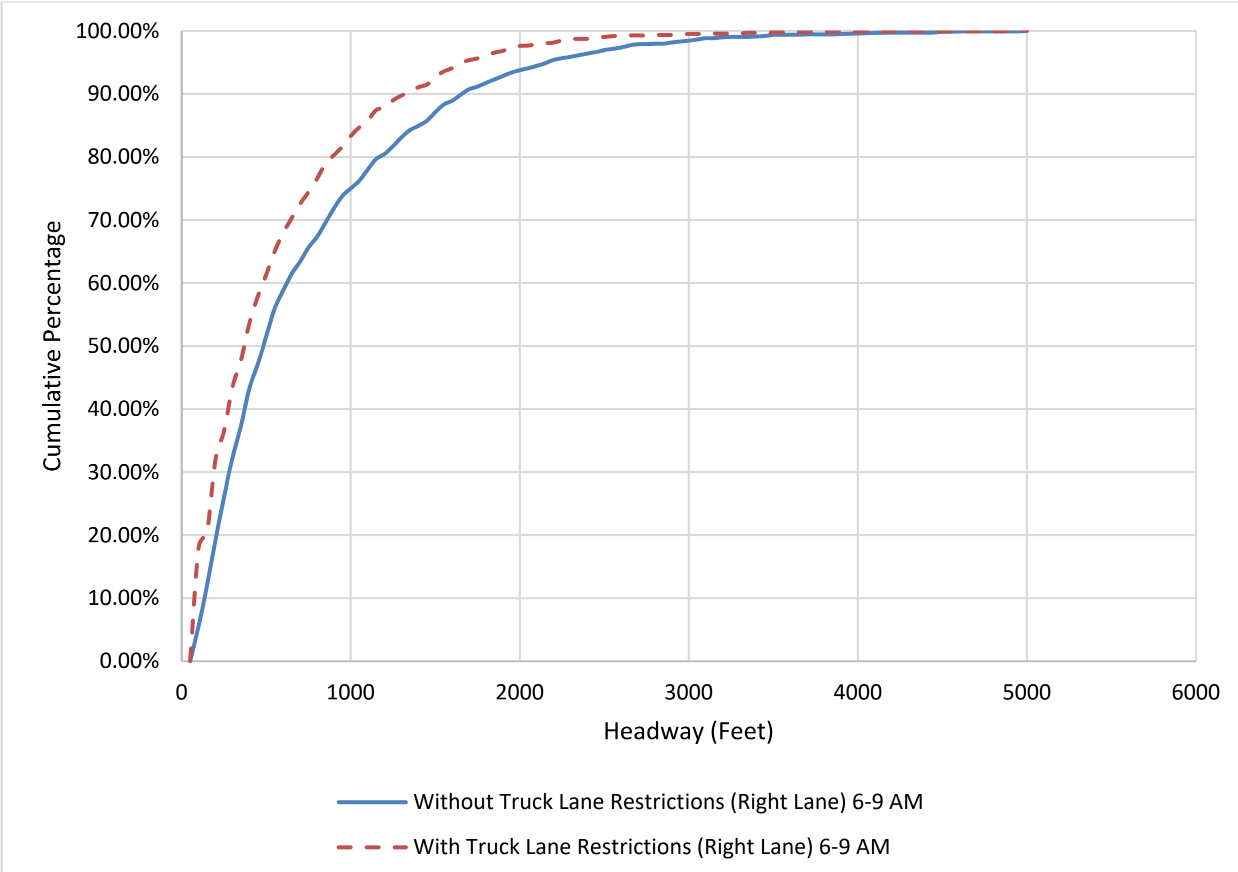


Figure 13. SB I-75 Cumulative headway distribution plot (right lane)—*without* vs. *with* condition (6–9 a.m.).

5.5.1.2 SB US -23 Location

Tables 15 and 16 summarize the K-S test results of *without* and *with* implementation of truck lane restrictions. The following discusses the headway analysis comparison for the right lane and left lane.

SB US-23 Headway Analysis Results Using K-S Test - Left Lane

Figure 14 presents a visual performance comparison of headway distribution through a cumulative distribution function in the morning peak period for the *without* vs. the *with* implementation periods of truck lane restrictions on the SB left lane. A shift in the headway distribution toward longer headways during the *with* condition was observed. At the headway of 100 ft, the cumulative percentages are 29.58% and 45.47% during the *with* condition and the *without* condition, respectively. The with condition had longer headways in approximately 55% of the sample (cumulative percentage 45% to 100%) with a maximum headway difference of 400 ft. The median value of headway was 104 ft during the *without* condition as opposed to 167 ft during the *with* condition. With the significance level α of 0.05 and the sample size of 5,993 during the *without*" condition and 3,374 during the *with* condition, the critical statistic of the K-S test for the maximum difference between the cumulative distributions, *D*, was 0.04. The results of the K-S test for the *without* condition vs. the *with* condition shows a value of *D* of 0.194 (greater than the critical value of 0.04), which suggests the differences in the two cumulative distributions are statistically significant.

Table 15. SB US-23 Headway analysis results using K-S test—left lane.

	Conditions	
	Without implementation of truck lane restrictions	With implementation of truck lane restrictions
Volume (Vehicle/3-hr)	**5,993**	**3,374**
Mean Headway (ft)	**166**	**277**
Median Headway (ft)	**104**	**167**
Maximum difference (*D*)	**0.194**	
Significance	**Yes**	

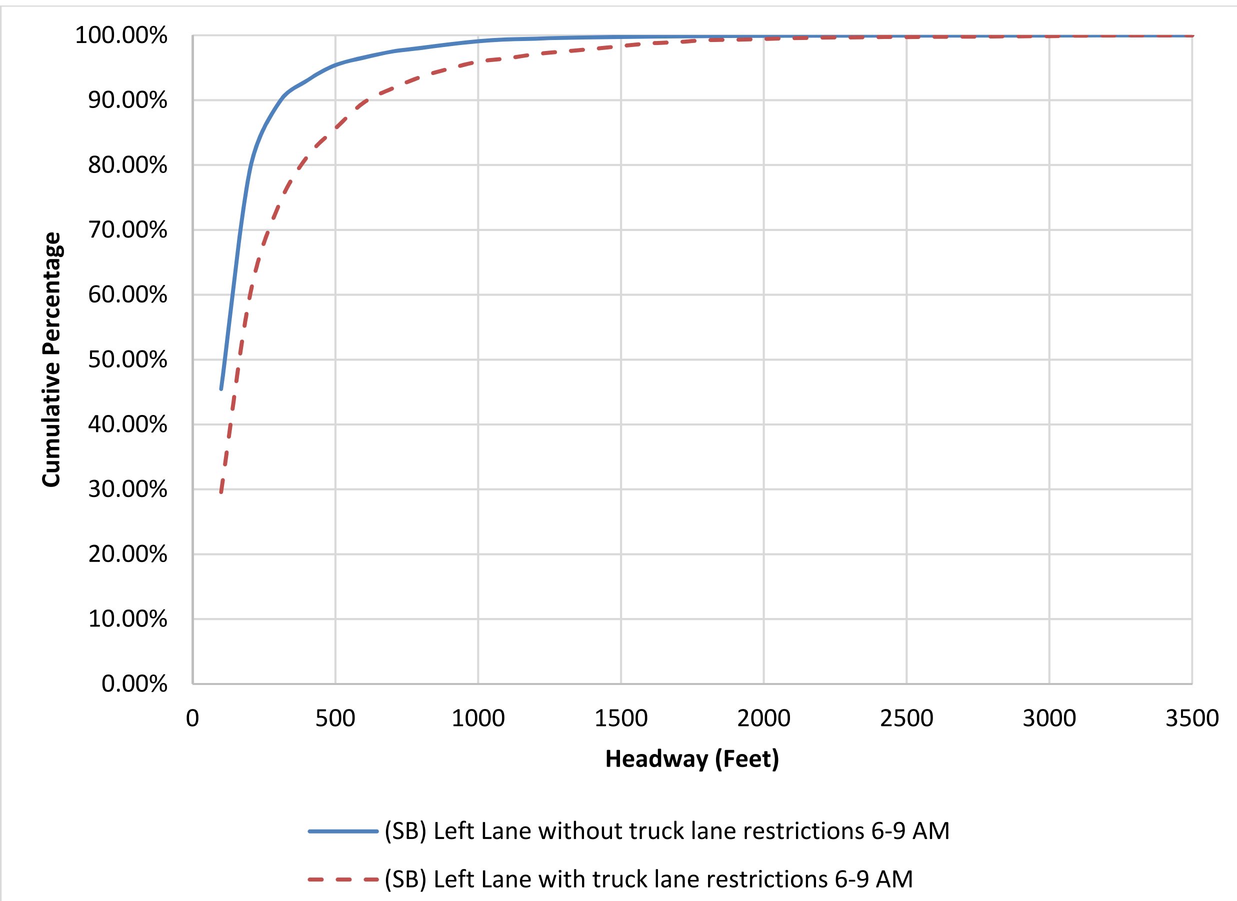


Figure 14. SB US-23 Cumulative headway distribution plot (left lane)—*without* vs. *with* condition (6–9 a.m.).

SB US-23 Headway Analysis Results Using K-S Test—Right Lane

Figure 15 presents a visual performance comparison of headway distributions through cumulative distribution function in the morning peak period for the *without* condition vs. the *with* condition on the SB right lane. A slight shift in the headway distribution toward longer headways during the *with* condition was observed. The *with* condition has a longer headway in approximately 25% of the sample (cumulative percentage 75% to 100%) with a maximum headway difference of 100 ft. The median value of headway was 211 ft at the *without* condition as opposed to 229 ft at the *with* condition. With the significance level α of 0.05 and the sample size of 3,094 during the *without* condition and 2,883 during the *with* condition, the critical statistic of K-S test for the maximum difference between the cumulative distributions, D, is 0.04. The results of K-S test for the *without* condition vs. the *with* condition shows a value of D of 0.02 (less than the critical value of 0.04), which suggests the differences in the two cumulative distributions are not statistically significant.

Table 16. SB US-23 Headway analysis results using K-S test—right lane.

	Conditions	
	Without implementation of truck lane restrictions	**With implementation of truck lane restrictions**
Volume (Vehicle/3-hr)	**3,094**	**2,883**
Mean Headway (ft)	**305**	**326**
Median Headway (ft)	**211**	**229**
Maximum difference (D)	**0.023**	
Significance	**No**	

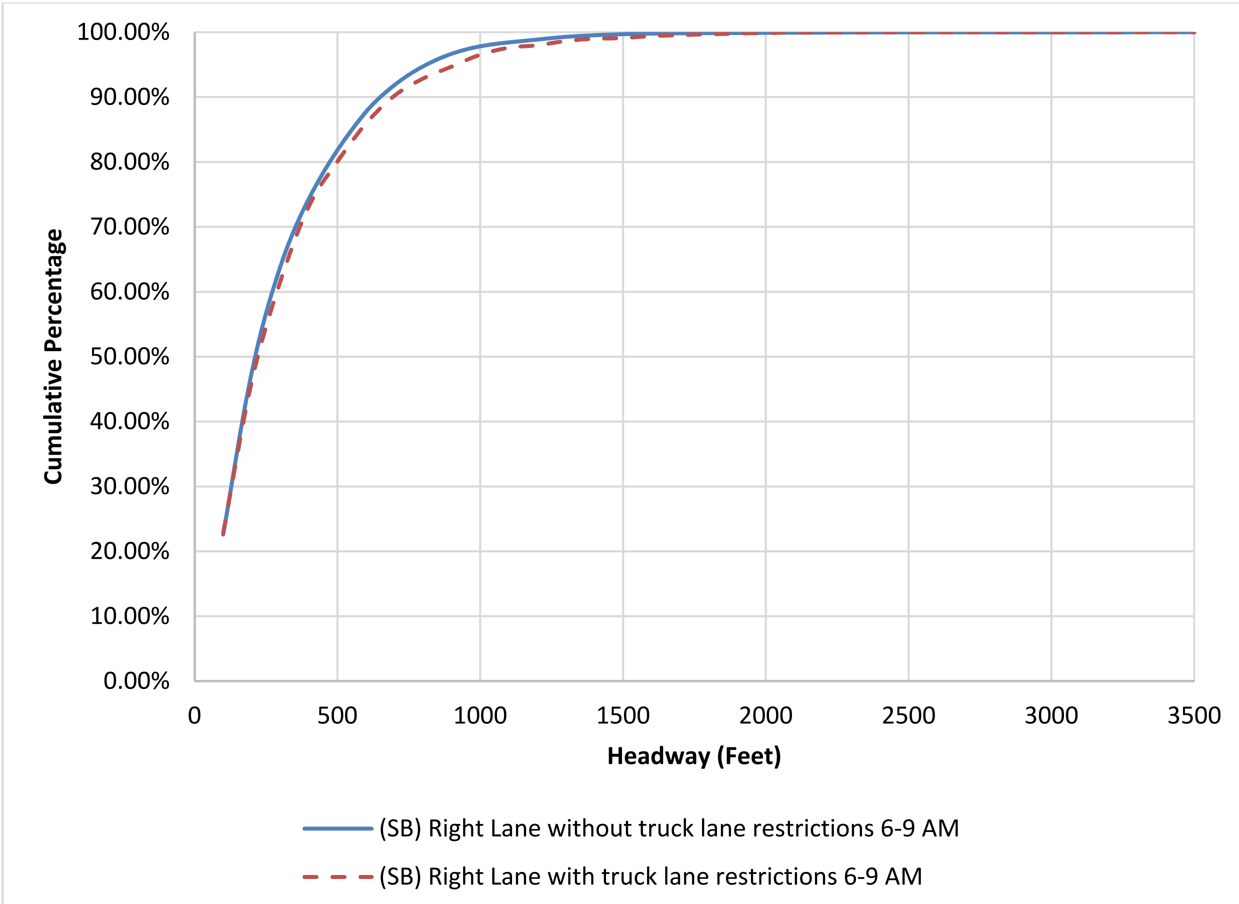


Figure 15. SB US-23 Cumulative headway distribution plot (right lane)—*without* vs. *with* condition (6–9 a.m.).

5.5.1.3 NB US -23

Tables 17 and 18 summarize the K-S test results of *without* and *with* implementation of truck lane restrictions. A discussion of the headway analysis comparison for the right lane and left lane follows.

NB US-23 Headway Analysis Results Using K-S Test—Left Lane

Figure 16 presents a visual performance comparison of headway distribution through cumulative distribution function in the morning peak period for *without* vs. *with* implementation of truck lane restriction on the NB left lane. The agency observed a slight shift in the headway distribution toward longer headway during the *with* condition. The *with* condition had a longer headway in an approximately 15% of sample (cumulative percentage 85% to 100%) with a maximum headway difference of 500 ft. The median value of headway was 167 ft during the *without* condition as opposed to 141 ft during the *with* condition. With the significance level α of 0.05 and the sample size of 4,036 during the *without* condition and 2,359 during the *with* condition, the critical statistic of K-S test for the maximum difference between the cumulative distributions, D, is 0.04. The results of K-S test for the *without* condition vs. the *with* condition shows a value of D of 0.049 (greater than the critical value of 0.04), which suggests the differences in the two cumulative distributions are statistically significant.

Table 17. NB US-23 Headway analysis results using K-S test–left lane.

	Conditions	
	Without implementation of truck lane restrictions	**With implementation of truck lane restrictions**
Volume (Vehicle/3-hr)	**4,036**	**2,359**
Mean Headway (ft)	**226**	**270**
Median Headway (ft)	**167**	**141**
Maximum difference (D)	**0.049**	
Significance	**Yes**	

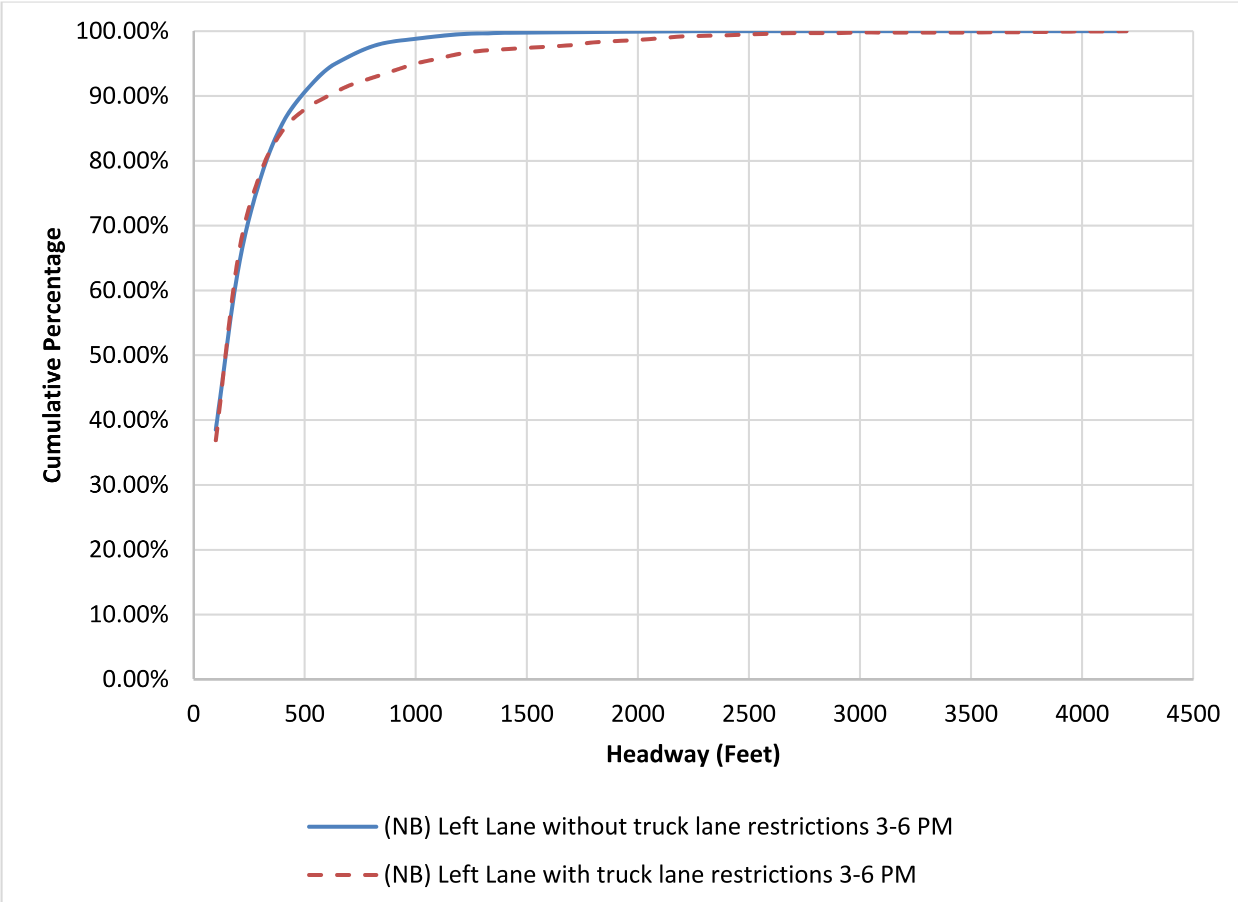


Figure 16. NB US-23 Cumulative headway distribution plot (left lane)—*without* vs. *with* condition (3–6 p.m.).

NB US-23 Headway Analysis Results Using K-S Test—Right Lane

Figure 17 presents a visual performance comparison of headway distribution through cumulative distribution function in the morning peak period for the *without* condition vs. the *with* condition on NB right lane. The agency observed a shift in the headway distribution toward longer headways during the *without* condition. At the headway of 100 ft, the cumulative percentages are 39.41% and 21.98% during the *with* condition and the *without* condition, respectively. The *without* condition had a longer headway in an approximately 55% of sample (cumulative percentage 40% to 95%) with a maximum headway difference of 300 ft. The median value of headway was 246 ft at the *without* condition as opposed to 339 ft at the *with* condition. With the significance level α of 0.05 and the sample size of 2,411 during the *without* condition and 3,139 during the *with* condition, the critical statistic of K-S test for the maximum difference between the cumulative distributions, D, is 0.04. The results of K-S test for the *without* condition vs. the *with* condition shows a value of D of 0.277 (greater than the critical value of 0.04), which suggests the differences in the two cumulative distributions are statistically significant.

Table 18. NB US-23 Headway analysis results using K-S test—right lane.

	Conditions	
	Without implementation of truck lane restrictions	**With implementation of truck lane restrictions**
Volume (Vehicle/3-hr)	**2,411**	**3,139**
Mean Headway (ft)	**354**	**339**
Median Headway (ft)	**246**	**339**
Maximum difference (D)	**0.277**	
Significance	**Yes**	

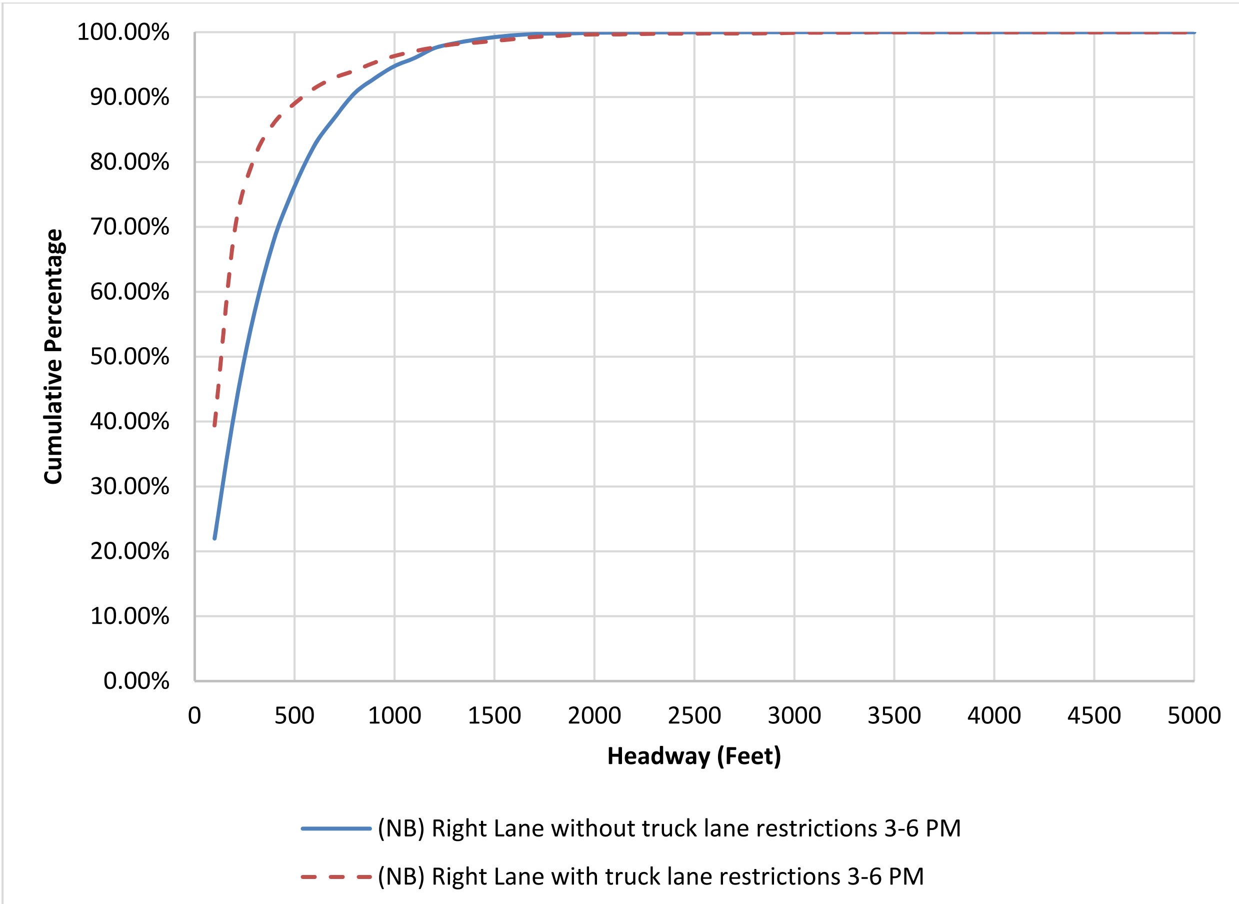


Figure 17. NB US-23 Cumulative headway distribution plot (right lane)—*without* vs. *with* condition (3–6 p.m.).

5.5.2 Comparison of Results for Platoon Headways and Gap Acceptance

The team examined the number of instances where a vehicle leads a platoon of traffic. A platoon is defined as a vehicle traveling with a headway greater than 3 seconds, followed by one or more vehicles with a headway less than 3 seconds. In this analysis, the headway was analyzed for different vehicle leader–follower pairs—car followed by a car or truck (C-C and C-T) and a truck followed by a car or truck (T-C and T-T).

Table 19 shows the results of the mean headways and gap acceptance for the different vehicle pairs *without* and *with* truck lane restrictions at the SB I-75 test site. It is noted that data were presented for evening peak period (3–6 p.m.) only, which happened to have the highest traffic volumes during the day.

The results show that the mean headways in the left lane increased for C-C (by 1.9%), C-T (by 13.2%), and T-T (by 2.3%) pairs, and decreased for T-C pairs (by 0.9%). Correspondingly, the mean gaps in the left lane decreased for C-C (by 4.5%), T-C (by 8%), and T-T (by 8.1%) pairs and increased for T-C pairs (by 5.6%).

In the right lane, the mean headways decreased (by 16.1% for C-C, 11.1% for C-T, 6.7% for T-C, and 4.4% for T-T) for all vehicle pairs and the mean gaps increased for all vehicle pairs (by 0.2% for C-C, 5.6% for C-T, 8.8% for T-C, and 24.4% for T-T). The decrease in headways in the right lane was expected as the volume of passenger cars in the right lane increased when the truck restrictions were in place. However, it is noted that, in theory, trucks should not be using the right lane in the *after* condition, as the restrictions were in place. The presence of trucks in the right lane can be attributed to trucks not complying with the restrictions, as well as trucks making lane change maneuvers to exit.

Table 20 shows the results of the mean headways and gap acceptance for the different vehicle pairs *without* and *with* truck lane restrictions at the SB US-23 test site. It is noted that data were presented for morning peak period (6–9 a.m.) only, which happened to have the highest traffic volumes during the day. The results show that the mean headways in the left lane increased for C-C (by 14.1%), C-T (by 38.9%), T-C (by 23.6%), and decreased for T-T (by 67.6%). Correspondingly, the mean gaps in the left lane also increased for C-C (by 14.4%), T-C (by 35.9%), and T-C (by 20.8%) pairs, and decreased for T-T pairs (by 66.5%).

In the right lane, the mean headways increased for C-C (by 6.1%), C-T (by 7.5%), T-C (by 5.8%), and decreased for T-T (by 7.6%) pairs. The mean gaps also increased for all vehicle pairs (by 5.5% for C-C, 12.3% for C-T, 10.1% for T-C, and 1.9% for T-T).

Table 21 shows the results of the mean headways and gap acceptance for the different vehicle pairs *without* and *with* truck lane restrictions at the NB US-23 test site. It is noted that data were presented for evening peak period (3–6 p.m.) only, which happened to have the highest traffic volumes during the day.

The results show that the mean headways in the left lane decreased for all vehicle pairs (by 26.2% for C-C, 34.4% for C-T, and 7.5% for T-C). Correspondingly, the mean gaps in the left lane also increased for C-C (by 24%), C-T (by 20.5%), and T-C (by 32.2%) pairs. T-T vehicle interactions were not found within the evening peak period (3–6 p.m.).

In the right lane, the mean headways decreased for all vehicle pairs (by 43.9% for C-C, 27.6% for C-T, and 19% for T-C, and 4.7% for T-T). The mean gaps also decreased for all vehicle pairs (by 19.1% for C-C, 18.7% for C-T, 7.8% for T-C, and 10.1% for T-T).

Table 19. SB I-75 Platoon headways and gap acceptance (3–6 p.m.).

Lane	Headway Type	% of Trucks			Average Speed (mph)			Sample Size		Mean Headway (ft)			Mean Gap (sec)		
		Without	With	Difference (%)	Without	With	Difference (%)	Without	With	Without	With	Difference (%)	Without	With	Difference (%)
Left Lane	C-C	12.62	23.87	+89.2	56.3	59.3	+5.3	2,034	1,568	299.1	304.7	1.9	3.55	3.39	-4.5
	C-T							82	148	303.4	343.3	13.2	3.78	3.99	5.6
	T-C							700	940	287.4	284.7	-0.9	3.74	3.44	-8.0
	T-T							128	296	320.9	328.2	2.3	4.34	3.99	-8.1
Right Lane	C-C	36.42	9.51	-73.9	67	58	-13.4	748	1790	417.9	350.5	-16.1	4.06	4.07	0.2
	C-T							206	58	474.3	421.5	-11.1	4.78	5.05	5.6
	T-C							570	266	376.9	351.8	-6.7	3.97	4.32	8.8
	T-T							262	26	415.1	433.3	4.4	4.47	5.65	26.4

Table 20. SB US-23 Platoon headways and gap acceptance (6–9 a.m.).

Lane	Headway Type	% of Trucks			Average Speed (mph)			Sample Size		Mean Headway (ft)			Mean Gap (sec)		
		Without	With	Difference (%)	Without	With	Difference (%)	Without	With	Without	With	Difference (%)	Without	With	Difference (%)
Left Lane	C-C	1.49	8.16	+449.4	64.04	65	+1.5	2,690	2,154	2,90.6	331.6	14.1	2.99	3.42	14.4
	C-T							30	116	297.2	412.7	38.9	3.23	4.39	35.9
	T-C							104	396	287.2	355.1	23.6	3.17	3.83	20.8
	T-T							4	36	NA*	366.2	NA*	NA*	4.19	NA*
Right Lane	C-C	13.74	8.03	-41.6	59.9	60.5	+1.0	2,104	2,258	291.2	308.9	6.1	3.28	3.46	5.5
	C-T							94	90	374.7	402.8	7.5	4.13	4.64	12.3
	T-C							598	284	306.9	324.8	5.8	3.68	4.05	10.1
	T-T							68	28	353.4	326.7	-7.6	4.13	4.21	1.9

* Small data sample

Table 21. NB US-23 Platoon headways and gap acceptance (3–6 p.m.).

Lane	Headway Type	% of Trucks			Average Speed (mph)			Sample Size		Mean Headway (ft)			Mean Gap (sec)		
		Without	With	Difference (%)	Without	With	Difference (%)	Without	With	Without	With	Difference (%)	Without	With	Difference (%)
Left Lane	C-C	2.13	10.95	+415.2	58.2	34.8	-40.2	3,298	1,576	268.9	198.5	-26.2	3.12	3.87	24.0
	C-T							44	62	337.9	221.6	-34.4	3.95	4.76	20.5
	T-C							120	338	276.1	255.3	-7.5	3.45	4.56	32.2
Right Lane	C-C	13.17	5.96	-54.7	53.9	36.7	-31.9	1,660	2,806	301.7	169.3	-43.9	3.76	3.04	-19.1
	C-T							90	98	339.4	245.6	-27.6	4.44	3.61	-18.7
	T-C							392	290	296.8	240.3	-19.0	4.0	3.69	-7.8
	T-T							40	14	324.7	309.4	-4.7	4.45	4	-10.1
No T-T interactions were found within the evening peak period (3–6 p.m.).															

5.6. Work Zone Crash Modification Factor for Truck Lane Restrictions

This section discusses the CMF calculation for deploying truck lanes. Table 22 shows the expected and actual crash results for the deployment of truck lane. The Total Hours column indicates the number of hours of data analyzed.

Table 22. Expected and actual crash results for truck lane restriction.

Treatment	Total Hours	Expected Crashes	Actual Crashes	Percent Change
Truck Lane Deployment	5,880	695.3	449	-35

For truck lane deployment condition, there was a 35% decrease from expected to actual crashes. In order to determine the proportional effects of the treatments on the numbers of crashes, an odds ratio analysis was undertaken according to the following equations:

$$CMF_D = \frac{TA_D TE_{ND} / TE_D TA_{ND}}{(1 + 1/TE_{ND} + 1/TE_D + 1/TA_{ND})}$$

$$SE(CMF_D) = \sqrt{\frac{CMF_D^2\,(1/TA_D + 1/TE_{ND} + 1/TE_D + 1/TA_{ND})}{(1 + 1/TE_{ND} + 1/TE_D + 1/TA_{ND})}}$$

Where:

CMF_D = crash modification factor = proportional effect of a deployment on crashes:

TA_D = total actual crashes during a deployment (equal to 449 in this case);

TE_D = total expected crashes during a deployment (equal to 695.3 in this case);

TA_{ND} = total actual crashes when nothing was deployed (equal to 425 in this case);

TE_{ND} = total expected crashes when nothing was deployed (equal to 614.3 in this case); and

SD (CMF_D) = standard error.

Table 23 shows the results from the CMF calculation. The calculated CMF for the deployment of truck lane is less than 1, indicating that this treatment had only minor effect on reducing the number of crashes, without taking standard error into account.

Table 23. CMF results for truck lane restriction.

Treatment	CMF_D	$SE(CMF_D)$	ADT
Truck Lane Deployment (Interstate)	0.928	0.081	Up to 100,000 Vehicles

The CMF is limited because of the few test sites. Agencies should use this as a guide, and monitor all work zones and take appropriate action to mitigate any increase in crashes (i.e., severity and number).

6.0 Field Evaluation of Temporary Ramp Metering

Many regions have deployed, sustained, and expanded ramp metering to improve daytime traffic operations on freeways. It is a proven and efficient tool to address traffic congestion and safety issues; however, it is a challenge to use under work zone conditions. Agency support and project costs also pose difficulties for state/local transportation agencies. There are very few state DOTs (Minnesota and Pennsylvania) that use ramp metering to improve the overall work zone mobility and safety and even then, it is rarely used. There is only one comprehensive study on the use of ramp metering in work zones and that evaluation was performed during off-peak conditions for the Missouri Department of Transportation. The focus of this report is to present results from the evaluation of ramp metering conducted during peak conditions in the United States and add to the body of knowledge on available strategies for improving mobility and safety in work zones.

6.1. Site Selection and Characteristics

Through outreach efforts to state transportation agencies, the research team identified the following locations as test sites for evaluation:

- MN Route 52 Bridge Deck Replacement Project, Rochester, Minnesota.
- I-279 Parkway North Improvement Project, Ohio Township, Allegheny County, Pennsylvania.

6.1.1 MN Route 52 Bridge Deck Replacement Project, Rochester, Minnesota

This project evaluated the effectiveness of ramp metering in a work zone setting on a bridge deck replacement project. The project involved replacing the existing concrete bridge decks on the US 52 bridges over US 63 in Rochester. Additionally, Minnesota Department of Transportation (MnDOT) upgraded the US 52 northbound lane additions near the end of the bridge.

Construction narrowed US 52 traffic from two lanes in each direction to a single lane in each direction (Figure 18). MnDOT activated a ramp meter on the northbound US 63 entrance loop to northbound US 52 to help regulate traffic flow during construction. The ramp metering was in place from April 18 to July 1, 2016. The ramp meter operated only on weekdays between 7:30 to 8:30 a.m. and 4:00 to 5:00 p.m.

MnDOT chose to use ramp metering because of the exceedingly high ramp volumes averaging more than 900 vehicle per hour (vph) during the morning peak period (ramp ADT approximately 12,600), with corresponding mainline morning peak volumes of close to 1,100 vph (mainline ADT approximately 17,500). Overall, the ramp contributes as much as 42 percent of total traffic volume at this location. The work zone posted speed limit was 55 mph.

The northbound US 63 entrance loop at the point of merging with Highway 52 was allowed to form two lanes when merging. However, metering allowed only one car per green phase to merge onto the mainline. In addition to the appropriate ramp metering signs, MnDOT placed advance SIGNAL AHEAD warning signs (W3-3) on the ramp. The signal was roadside-mounted at a height of 10 ft with an 8-in. green, yellow, red lens/housing assembly (Figure 19).

The team collected data at four locations along the mainline (Route 52) near the interchange of MN Route 52/Route 63:

- **Location 1**, 2,600 ft upstream of on-ramp.
- **Location 2**, 800 ft upstream of on-ramp.
- **Location 3**, 400 ft downstream of on-ramp.
- **Location 4**, 3,000 ft downstream of on-ramp.

The team also installed two cameras at the northbound entering ramp to monitor traffic operations with and without ramp metering. The first camera installation was approximately 100 ft east of the gore area to monitor vehicle merging and weaving. The other camera installation was at the mid-point of the metered ramp to capture drivers' ramp-metering compliance. Figure 19 shows the ramp geometrics and layout of the data collection locations.

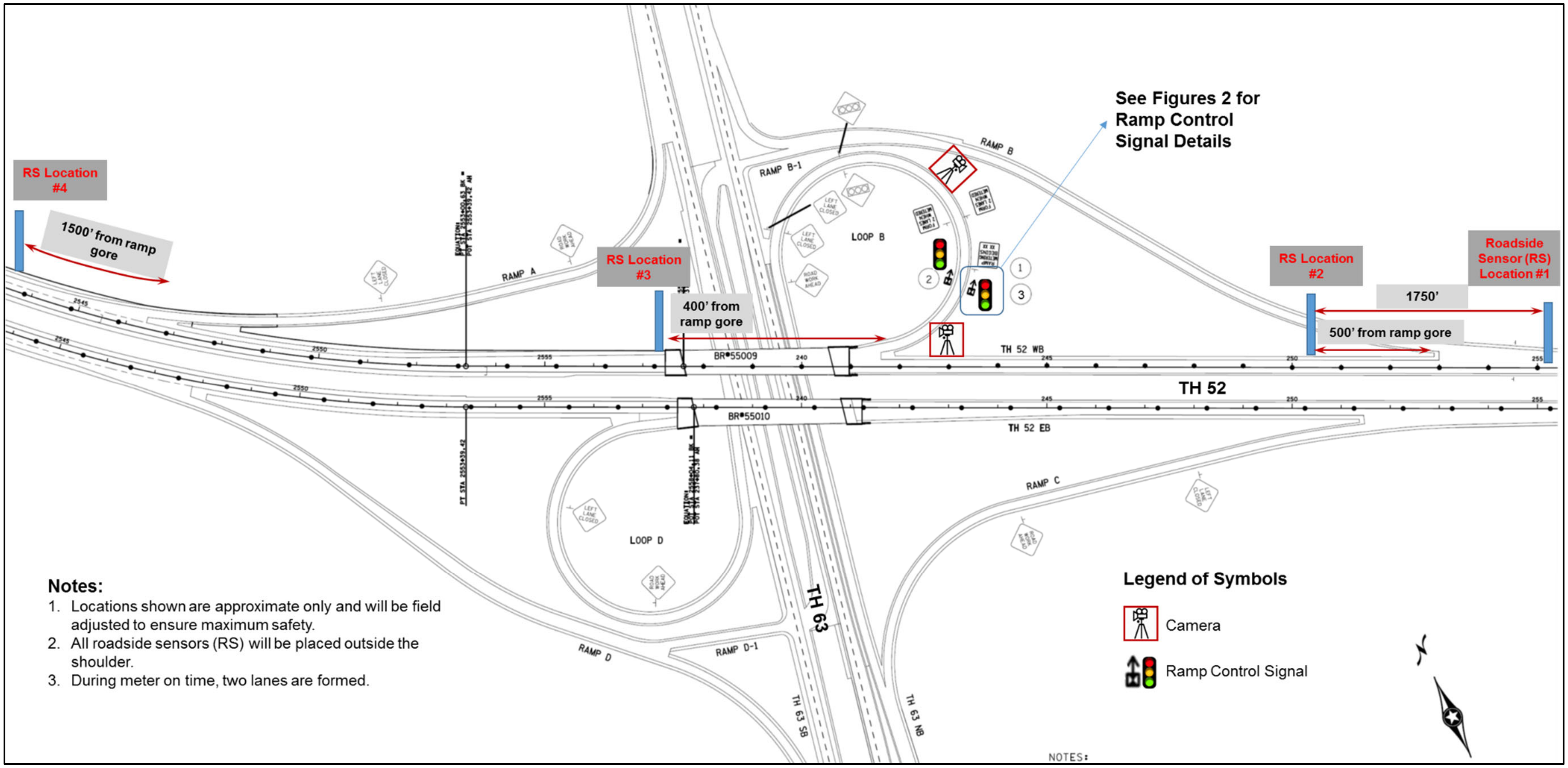


Figure 18. Ramp-metering data collection locations on MN Route 52 and Route 63 loop b ramp, Rochester, Minnesota.

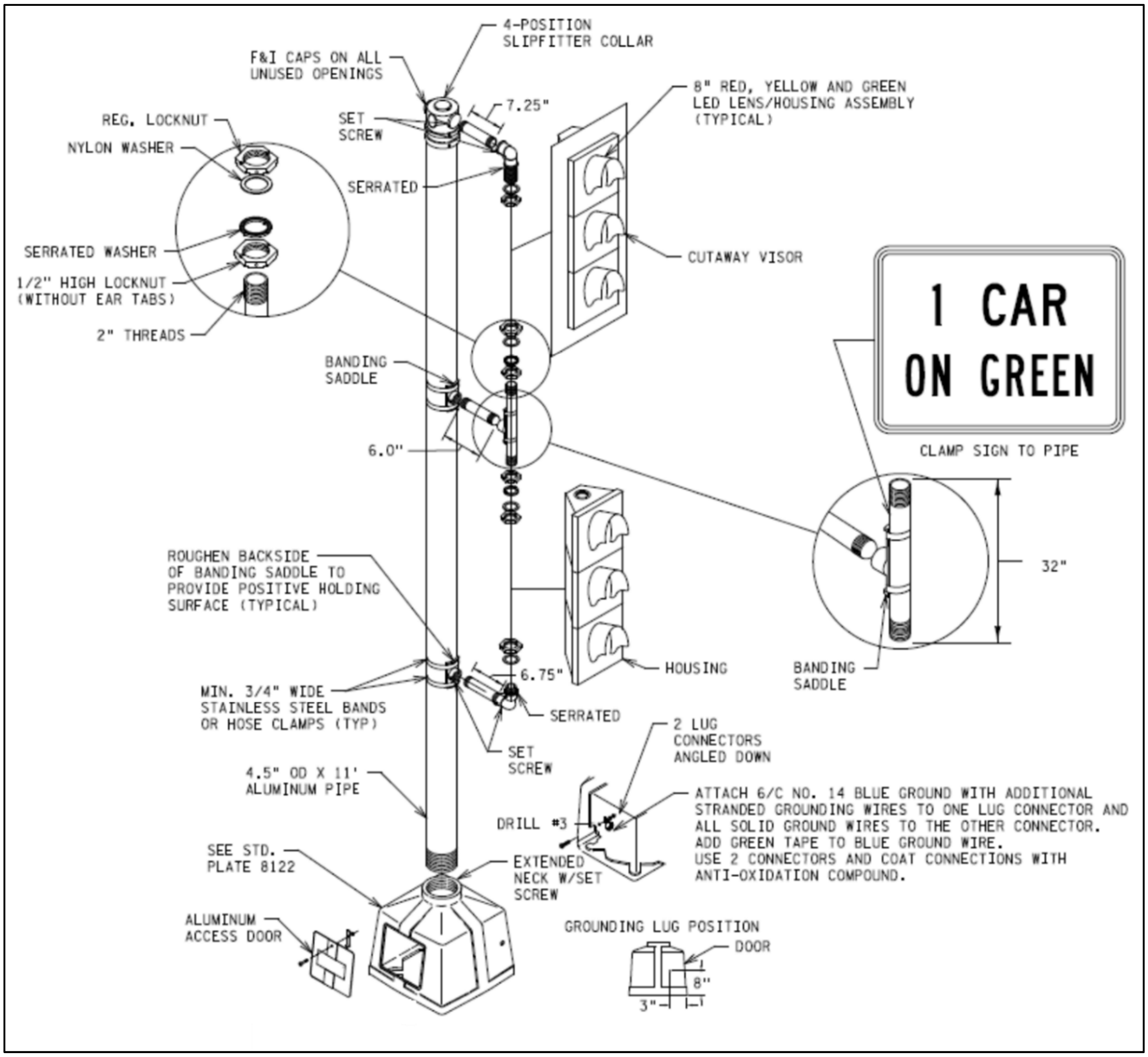


Figure 19. MnDOT ramp-control signal details.

6.1.2 I-279 Parkway North Improvement Project, Ohio Township, Allegheny County, Pennsylvania

This project included concrete patching and overlay, preservation of 30 bridges and 49 overhead sign structures, repairs to 29 walls, repairs to ramps, improving lighting, repairing HOV lanes, updating signs, improving guardrail and drainage, and installing an anti-icing system on McKnight Road. In the northbound direction, work included reconfiguring the ramp from northbound I-579 to northbound I-279, lengthening the northbound Perrysville and Madison on-ramps, and paving on Route 28 between Anderson Street and Chestnut Street. In the southbound direction, traffic was crossed over into the northbound lanes at the Camp Horne (Exit 8) interchange. Both southbound lanes were shifted into the HOV lanes at the Perrysville Avenue (Exit 5) interchange before reentering mainline I-279 south of McKnight Road. The project continued through June 2019.

To evaluate the effectiveness of ramp metering in a work zone, Pennsylvania Department of Transportation (PennDOT) revised its approved MOT plans to include ramp metering at Union Avenue entrance ramp to southbound I-279. This was made possible through a combined effort of the state DOT, FHWA, and the research team. The Union Avenue entrance ramp to southbound I-279 (two lanes) was best suited for metering based on an operational assessment conducted by PennDOT. The assessment indicated that ramp metering may help to regulate traffic flow through the heavily congested corridor during construction. Ramp volumes peaked at 450 vph with mainline volumes at 1,200/1,750 vph for the right lane and left lane, respectively.

The ramp metering was in place April 23–August 26, 2018. The ramp meter operated weekdays from 6:00–9:00 a.m. and 4:00–6:00 p.m.. Metering allowed only one car per green phase to merge onto the mainline. In addition to the appropriate ramp-metering signs, PennDOT placed advance SIGNAL AHEAD warning signs (W3-3) on the ramp. The signal support was roadside-mounted with the signal cantilevered over the road at a height of 14 ft with a green/red lens/housing assembly (Figure 20).

The team collected data at four locations along the mainline (I-279) near the interchange of Union Avenue:

1. **Location 1**, 5,250 ft upstream from the southbound entering ramp (gore area).
2. **Location 2**, 1,300 ft upstream from the southbound entering ramp (gore area).
3. **Location 3**, 1,150 ft downstream from the southbound entering ramp (gore area).
4. **Location 4**, 5,250 ft downstream from the southbound entering ramp (gore area).

The team also installed two cameras at the southbound entering ramp to monitor traffic operations with and without ramp metering. The first camera installation was approximately 600 ft south of the gore area to monitor vehicle merging and weaving. The second camera was installed at the mid-point of the metered ramp to capture drivers' compliance with the ramp metering. Figure 20 shows the ramp geometrics and layout of the data collection locations.

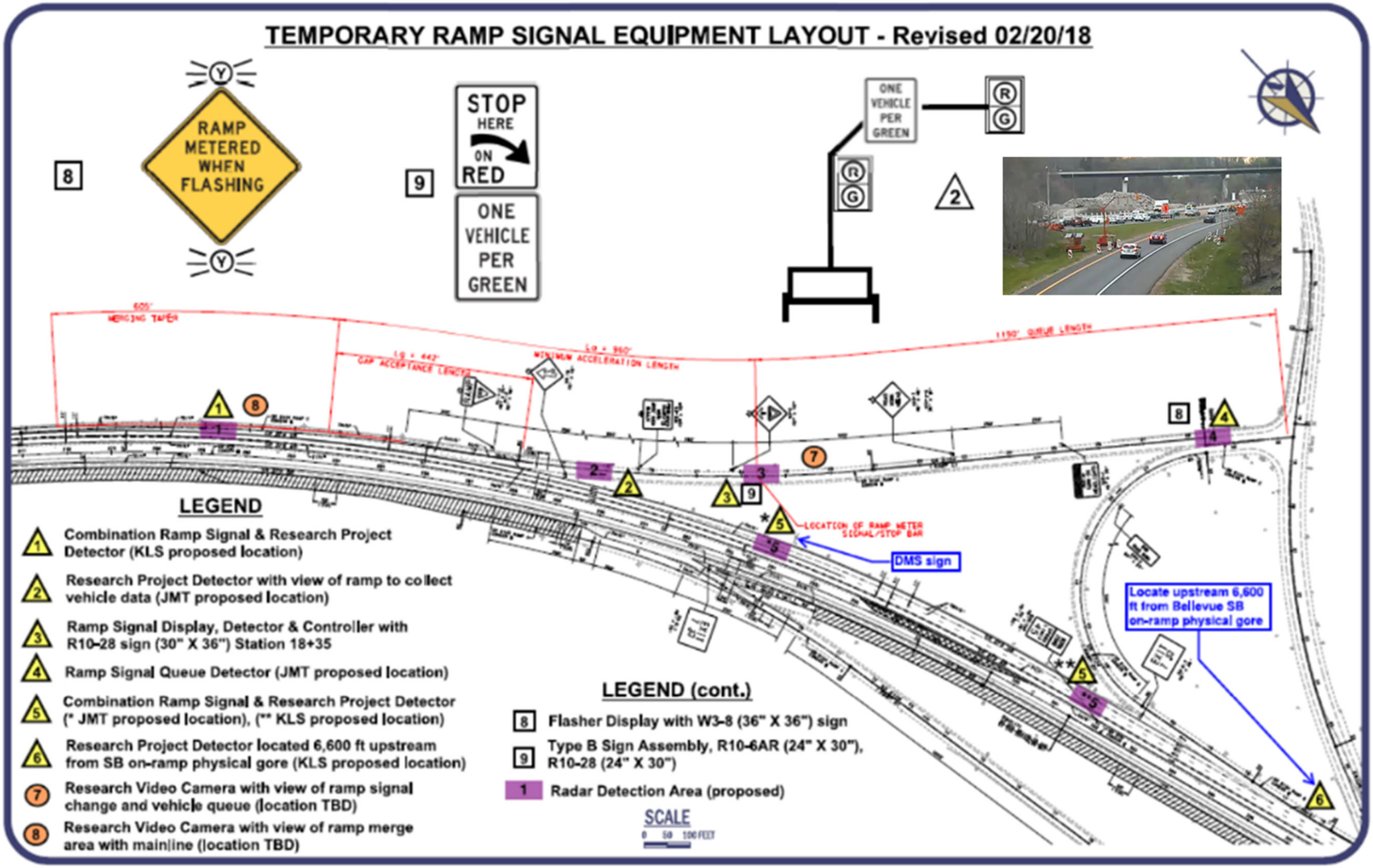


Figure 20. Ramp-metering data collection locations on I-279 and Union Avenue Ramp, Ohio Township, Pennsylvania.

6.2. Study Methodology

6.2.1 Data Collection Duration

MN Route 52, Rochester, Minnesota. The team collected data for MN Route 52 westbound on weekdays during three periods—meter on (fixed-cycle length), meter off, and meter on (variable-cycle length). Data were collected with meter on (fixed-cycle length) from May 17 to May 20, and with the meter off from May 21 to May 29, 2016. The team then changed the meter flow rate algorithm and collected data again with meter on (variable-cycle length) from May 30 to June 3, 2016. The ramp meter was set for operation during peak hours (a.m. peak, 7:30–8:30 a.m.) and (p.m. peak, 4:00–5:00 p.m.).

I-279, Ohio Township, Pennsylvania. The team collected data for I-279 southbound (both right lane and left lane) on weekdays during three periods—meter off, meter on (fixed-cycle length), meter on (variable-cycle length). Meter-off data were collected from April 23 to May13, 2018, and with Meter on (fixed-cycle length) from May 14 to June 4, 2018. The team collected meter on (variable-cycle length) data from June 5 to August 26, 2018. The ramp meter was set for operation during peak hours (6:00 a.m. to 9:00 a.m.) and (4:00 p.m. to 6:00 p.m.).

Because the most congested peak period at both study areas was a.m. peak, the traffic analyses of this study focused on the a.m. peak period only. Ramp traffic volumes in p.m. peak period were insignificant.

6.2.2 Data Collection Procedures

The team used Wavetronix sensors to collect vehicular data. Wavetronix sensors collect data by emitting a microwave radar beam. The sensors were trailer-mounted and stationed perpendicular to the roadway, outside the clear zone; as vehicles pass through the beam, the sensor detects the reflected microwave beam. The sensors can detect volume, vehicle classification, speed, 85th percentile speeds, and vehicle gaps across multiple lanes (up to 200 ft).

All vehicular data were collected by direction and by lane. The team measured the following data per lane: volume, speed, vehicle classification, headway, and gap. The data were collected in 1-minute bins.

The team screened all raw data to exclude missing data values and outliers such as vehicles traveling at very low or very high speeds. Data were analyzed separately for passenger cars and commercial vehicles.

6.2.3 Measures of Effectiveness

The team evaluated the following operational MOEs:

- **Vehicle speeds along mainline *with* and *without* ramp metering**. Because the intent is that ramp metering will control the flow rate of vehicles entering the main line, this treatment may increase vehicle operating speeds on the mainline.
- **Travel time through the work zone *with* and *without* ramp metering.** Travel time through a work zone is a measurement to determine the operational effect of implementing ramp metering. In this study, the team used locations 1 and 3 as the reference points to determine the travel time. As stated previously, because the intent is that ramp metering will control the flow rate of vehicles entering the main line, this treatment may reduce vehicle travel time through the corridor.
- **Merging headways *with* and *without* ramp metering.** Vehicle headway is a measure of the temporal space between two vehicles. As the average of vehicle headways is the reciprocal of flow rate, vehicle headways represent microscopic measures of flows passing a point. To some extent, the minimum acceptable mean headway determines the roadway capacity.
- **Driver compliance rates.** Visually process videos of ramp traffic. A vehicle is said to have complied with the ramp metering if it went through when the signal display is green.

6.2.4 Method for Statistical Test for Vehicle Speeds

The method for statistical test for vehicle speeds is the same as described in Section 5.2.5.

6.2.5 Method for Statistical Test for Travel Time through the Work Zone

Similar to the analysis of the vehicle speeds, the team used the *t*-test to compare the differences between the travel time through the work zone *with* and *without* the ramp metering. For the travel time analysis, the null and alternative hypotheses for testing the differences in two population travel time measures, μ_1 and μ_2, were:

- Null Hypothesis (H_0): There has been no change in mean travel time as a result of ramp metering, or H_0: $\mu_1 - \mu_2 = 0$.
- Alternative Hypothesis (H_a): There has been a change in mean travel time as a result of ramp metering, or H_a: $\mu_1 - \mu_2 > 0$.

At the study site, a *t*-statistic was calculated during data collection periods. Equation 3 in Section 5.2.5 shows the equation used to apply independent two-sample *t*-statistics to test for the difference between two sample means.

6.2.6 Method for a Statistical Test for Frequency of Headway

The statistical test for vehicle speeds is the same as described in Section 5.2.6.

6.2.7 Driver Compliance of Ramp Meter Signal

This analysis is to determine the percentage of vehicles that complied with the ramp metering signal. The team used videos, which captured ramp driver behavior to determine the number of vehicles traveling through the ramp when the signal display was green compared to the total number of vehicles going through the ramp during the test periods. The team determined the compliance rate by the number of vehicles in compliance divided the total number of vehicles traveling through the ramp during the test periods.

6.3. Comparison of Results for Vehicle Speeds

The team compared the vehicle speeds to evaluate the effect of ramp metering and to determine if ramp metering caused changes in travel characteristics. In this study, two ramp metering scenarios (Fixed-cycle length and Variable-cycle length) were compared to the *without* scenario. Implementing ramp metering was expected to have a positive effect on vehicle speeds on the mainline of a freeway at the vehicle-merging area. For this reason, the team analyzed vehicle speeds at the merge areas of the ramp and the mainline of the freeway.

6.3.1 MN Route 52, Rochester, Minnesota

The a.m. peak (6:00 to 9:00 a.m.) is the most congested peak period at the study area; therefore, the traffic analyses of this study focused on a.m. peak hour only. The team conducted an analysis of vehicle speeds on the mainline of the freeway at the merging area (location 3) during the a.m. peak period.

Figure 21 illustrates the vehicle speeds and traffic volumes on the main line for all scenarios. In general, it appears that ramp metering improved performance on the main line (i.e., vehicle speeds were higher for all meter-on scenarios (Options 1 and 2) during the a.m. peak hour period). What is also evident is that main line saturation was reached around 6:45 a.m., resulting in traffic flow breakdown prior to the ramp meter being turned on at 7:30 a.m. (to 8:30 a.m.). As expected, it took the ramp metering about 5–10 minutes to stabilize the traffic flow before any benefit could be realized, such as improvements in vehicle speed and travel time. However, greater benefits may have been realized if the ramp metering went into effect at 6:00 a.m., before the right lane flow reached its capacity of a combined 1,500–1,600 vehicles (with ramp volumes approaching 400–600 vehicles) per hour. This is much lower than the traditional traffic right lane volumes typically recommended for ramp metering at approximately 2,000 vph inclusive with ramp volumes approaching 400 vehicles per hour.

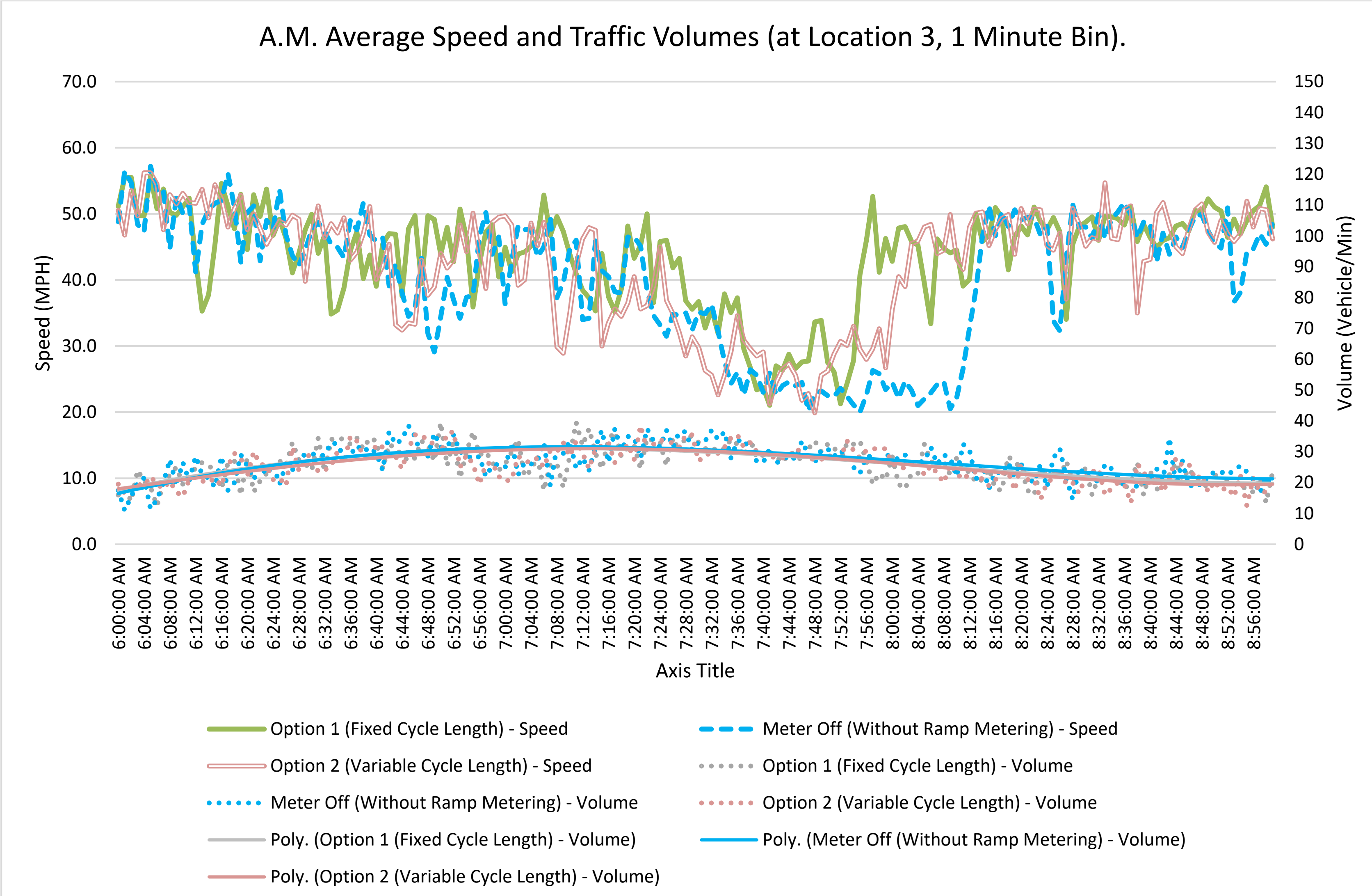


Figure 21. A.M. peak hour vehicle speed and traffic volumes at Location 3.

The changes in the mean speeds and 85th percentile speeds for vehicles *with* and *without* ramp-metering scenarios were calculated. Tables 24 and 25 show the comparison of mean speed and 85th percentile speed on the mainline and the statistical test results *with* and *without* ramp metering. The following section discusses both meter-on scenarios (fixed time vs. variable time).

6.3.1.1 Meter-off Scenario vs. Fixed-cycle Length Ramp Metering

As Table 24 shows, the mean speeds of vehicles on the mainline of the freeway increased for all time periods prior to 8:15 a.m.

Table 24. Speed comparison, meter-off and fixed-cycle length ramp metering.

Meter Off (Without Ramp Metering) and Option 1 (Fixed-cycle Length)								
	07:30 to 07:45		07:45 to 08:00		08:00 to 08:15		08:15 to 08:30	
	Meter off	Option 1	Meter off	Option 1	Meter off	Option 1	Meter off	Option 1
Volume (Vehicles/Time Periods)	450	471	418	436	403	360	342	332
Mean Speed (mph)	25.61	33.09	22.74	34.31	29.74	45.74	47.28	46.59
85th Percentile (mph)	28.17	42.60	26.30	46.04	46.09	50.38	55.20	51.64
SD	6.43	8.38	3.39	10.27	11.44	5.64	8.24	5.82
Mean Speed t_{static}	**-5.71**		**-7.48**		**-14.63**		0.69	

(Bold indicates significance at the 95% confidence level, α = .05)

Similar to the mean speeds, the 85th percentile speeds on the mainline of the freeway also increased for time periods prior to 8:15 a.m. The *t*-test results indicated that increases in mean speed during the fixed-cycle length ramp metering scenario were statistically significant for the time periods from 7:30 to 8:15 a.m.

6.3.1.2 Meter-off Scenario vs. Variable-cycle Length Ramp Metering

As Table 25 shows, the mean speeds of vehicles on the mainline of the freeway increased for all time periods from 7:30 to 8:30 a.m.

Table 25. Speed comparison, meter-off, and variable-cycle length ramp metering.

Meter off (Without Ramp Metering) and Option 2 (Variable-cycle Length)								
	07:30 to 07:45		07:45 to 08:00		08:00 to 08:15		08:15 to 08:30	
	Meter off	Option 2	Meter off	Option 2	Meter off	Option 2	Meter off	Option 2
Volume (Vehicles/Time Periods)	450	454	418	439	403	367	342	308
Mean Speed (mph)	25.61	27.20	22.74	26.37	29.74	44.82	47.28	48.52
85th Percentile (mph)	28.17	33.87	26.30	31.27	46.09	53.89	55.20	56.05
SD	6.43	6.51	3.39	5.51	11.44	9.47	8.24	7.61
Mean Speed t_{static}	**-2.86**		**-9.20**		**-16.55**		**-1.77**	

(Bold indicates significance at the 95% confidence level, α = .05.)

Similar to the mean speeds, the 85th percentile speeds on the mainline of the freeway also increased for all time periods from 7:30 to 8:30 a.m. The *t*-test results indicated the increases in mean speed during the variable-cycle length ramp metering scenario were also statistically significant for all time periods.

After implementing ramp metering, the speeds of vehicles on the mainline of the freeway increased in both scenarios. Therefore, it seems that implementing ramp metering has a positive effect, and although the changes varied, they were found to be statistically significant. What is also evident is that mainline saturation was reached around 6:30 a.m. and resulted in traffic flow breakdown prior to turning on the ramp meter. As expected, it took the ramp metering about 5–10 minutes to stabilize the traffic flow before any major benefit, such as improvements in vehicle speed, could be realized.

The ramp meter was turned on after mainline saturation; however, even at high ramp volumes (~900 vph), the system was able to generate approximately 5–9 mph increase in mainline speeds. The fixed-cycle length ramp-metering scenario worked best at such high ramp volumes, with a 28% (8.6 mph) increase in speed compared with variable-cycle length ramp metering scenario at 16.1% (5.18 mph) increase in speed.

6.3.2 I-279, Ohio Township, Pennsylvania

The most congested peak period at the study area was the a.m. peak; therefore, the traffic analyses of this study also focused on the a.m. peak hour only. The team conducted an analysis of vehicle speeds on the mainline (both right lane and left lane) of the freeway at the merging area (Location 3) during the a.m. peak period (5:30 to 10:00 a.m.).

Figures 22 and 23 illustrate the vehicle speeds and traffic volumes on the mainline for all scenarios. In general, it appears that ramp metering improved performance of the main lines (i.e., vehicle speeds were higher for all meter-on scenarios [Options 1 and 2] during the a.m. peak hour period). Mainline saturation was reached around 5:45 a.m. and resulted in traffic flow breakdown. After that, the ramp metering stabilized the traffic flow and major benefits (such as improved vehicle speed and travel time) were realized. The team observed significant improvements in vehicle speed and volume between 6:45 a.m. and 8:15 a.m. (Figures 24).

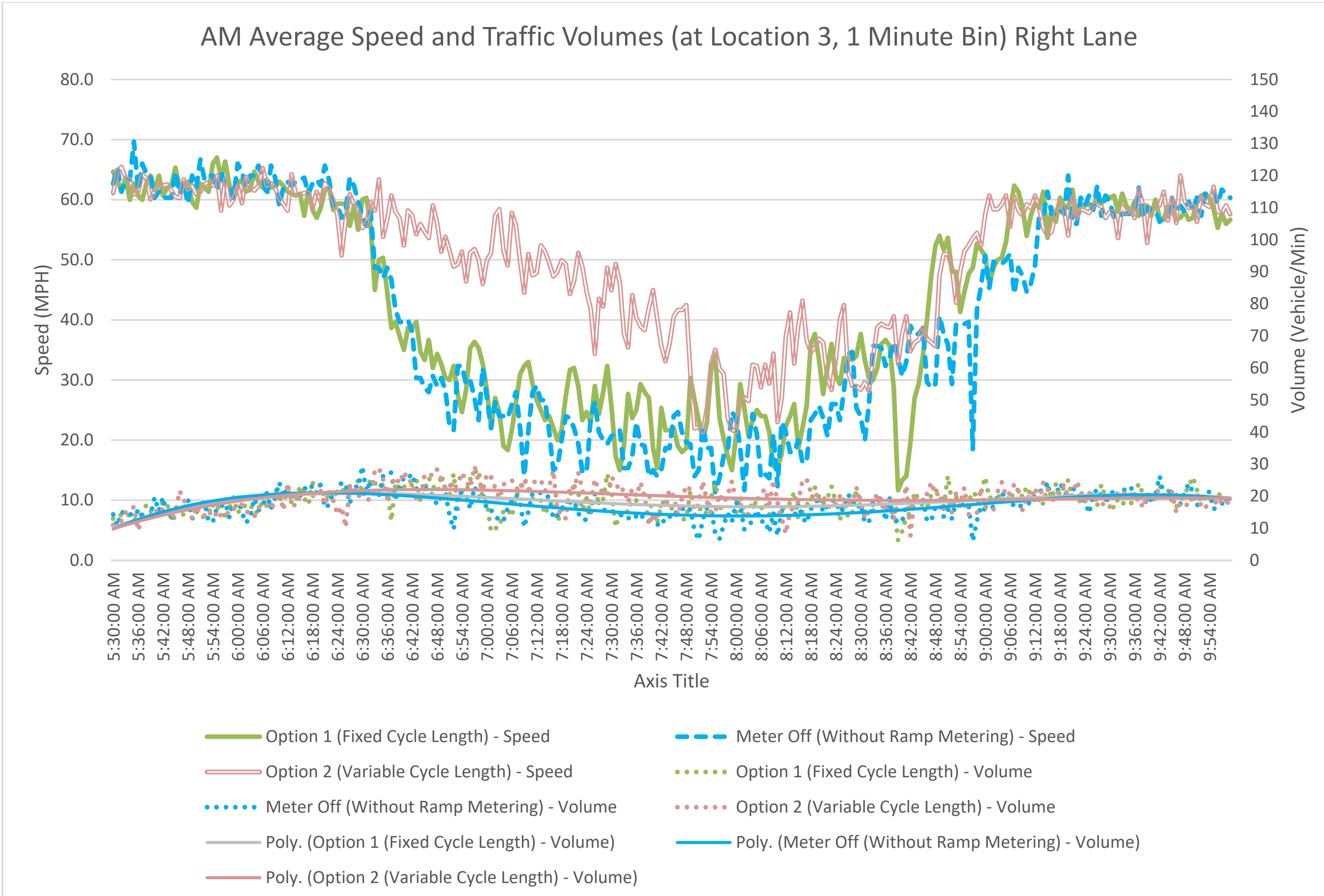


Figure 22. A.M. peak hour vehicle speed and traffic volumes at Location 3 (right lane).

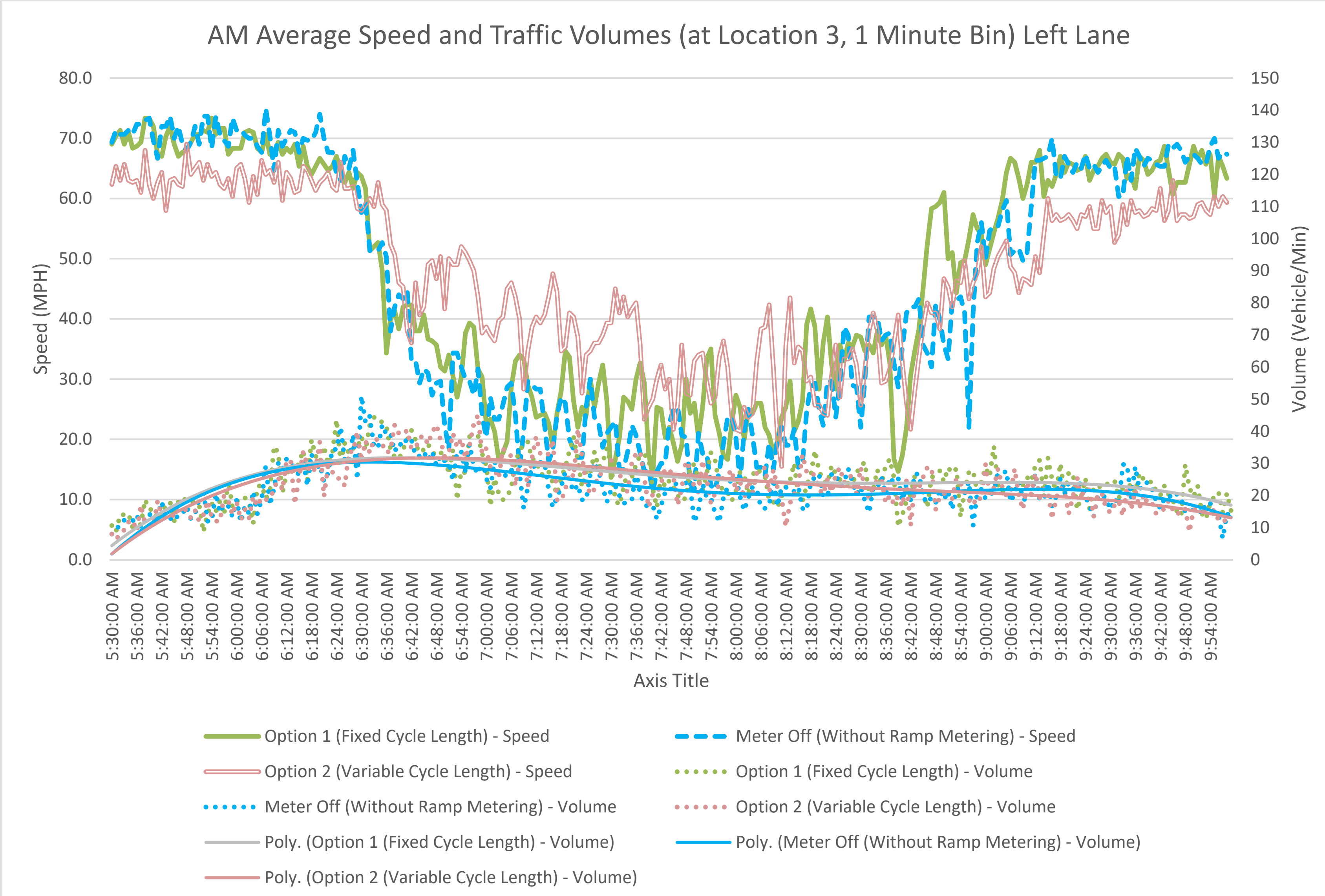


Figure 23. A.M. peak hour vehicle speed and traffic volumes at Location 3 (left lane).

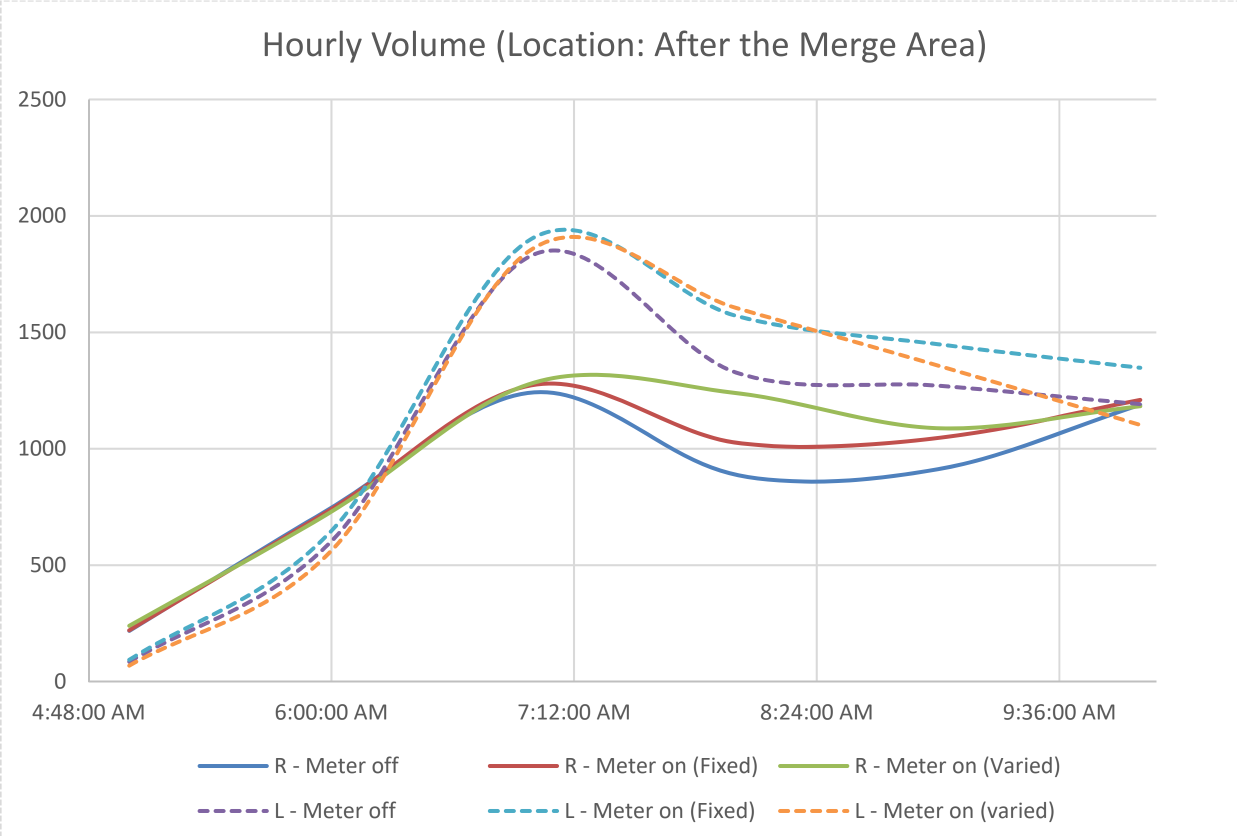


Figure 24. Hourly volume—Location 3, after the merge area.

The team calculated changes in the mean speeds and 85th percentile speeds for vehicles in the *with* and *without* ramp-metering scenarios. Tables 24 and 25 show the comparison of mean speed and 85th percentile speed of vehicles on the mainline (both right lane and left lane) of the freeway and the statistical test results with and without ramp metering. The following sections discuss both meter-on scenarios (fixed time vs. variable time).

6.3.2.1 Meter-off Scenario vs. Fixed-cycle Length Ramp Metering

As Tables 26 and 27 show, the mean speeds of vehicles on the mainline of the freeway increased for all time periods from 7:30 to 8:30 a.m. for both right lane and left lane.

Table 26. Speed comparison, meter-off scenario and fixed-cycle length ramp metering (right lane).

Meter off (Without Ramp Metering) and Option 1 (Fixed-cycle Length)								
	07:30 to 07:45		07:45 to 08:00		08:00 to 08:15		08:15 to 08:30	
	Meter Off	Option 1	Meter Off	Option 1	Meter Off	Option 1	Meter Off	Option 1
Volume (vehicles/time period)	200	255	190	240	195	245	252	266
Mean Speed (mph)	17.87	22.69	18.87	22.87	17.87	22.31	24.56	30.91
85th Percentile (mph)	24.80	30.00	26.40	32.00	24.80	30.20	33.00	48.00
SD	7.47	6.63	7.47	8.17	7.47	7.82	9.81	13.32
Mean Speed t_{static}	**-3.24**		**-2.42**		**-2.76**		**-2.58**	

(Bold indicates significance at the 95% confidence level, α = .05.)

Table 27. Speed comparison, meter-off scenario and fixed-cycle length ramp metering (left lane).

Meter Off (Without Ramp Metering) and Option 1 (Fixed-cycle Length)								
	07:30 to 07:45		07:45 to 08:00		08:00 to 08:15		08:15 to 08:30	
	Meter Off	Option 1	Meter Off	Option 1	Meter Off	Option 1	Meter Off	Option 1
Volume (vehicles/time period)	289	379	299	262	304	353	343	378
Mean Speed (mph)	17.49	23.31	18.42	23.33	18.87	23.67	26.69	33.02
85th Percentile (mph)	25.40	33.40	27.00	31.00	29.00	32.60	39.00	51.00
SD	8.29	7.75	7.93	8.64	8.51	8.90	11.91	14.75
Mean Speed t_{static}	**-3.44**		**-2.81**		**-2.62**		**-2.24**	

(Bold indicates significance at the 95% confidence level, α = .05.)

Similar to the mean speeds, the 85th percentile speeds on the mainline of the freeway also increased for time periods from 7:30 to 8:30 a.m. The *t*-test results indicated the increases in mean speed during the fixed-cycle length ramp metering scenario were statistically significant for the time periods from 7:30 to 8:30 a.m.

Overall, speeds increased in both right and left lanes, under the fixed-cycle length ramp metering scenario by 24% (4.8 mph) and 41 percent (8.34 mph), respectively. A larger increase in the left lane was expected as fewer vehicles try to merge across to the left lane.

6.3.2.2 Meter-off Scenario vs. Variable-cycle Length Ramp Metering

As Tables 28 and 29 show, the mean speeds of vehicles on the mainline of the freeway increased for all time periods from 7:30 to 8:30 a.m. for both right lane and left lane.

Table 28. Speed comparison, meter-off scenario and variable-cycle length ramp metering (right lane).

Meter Off (Without Ramp Metering) and Option 2 (Variable-cycle Length)								
	07:30 to 07:45		07:45 to 08:00		08:00 to 08:15		08:15 to 08:30	
	Meter Off	Option 2	Meter Off	Option 2	Meter Off	Option 2	Meter Off	Option 2
Volume (vehicles/time period)	200	293	190	287	195	255	252	297
Mean Speed (mph)	17.87	35.64	18.87	30.27	17.87	29.14	24.56	30.49
85th Percentile (mph)	24.80	56.40	26.40	45.20	24.80	43.85	33.00	45.80
SD	7.47	19.06	7.47	12.56	7.47	13.44	9.81	12.63
Mean Speed t_{static}	**-5.83**		**-5.23**		**-4.79**		**-2.49**	

(Bold indicates significance at the 95% confidence level, α = .05.)

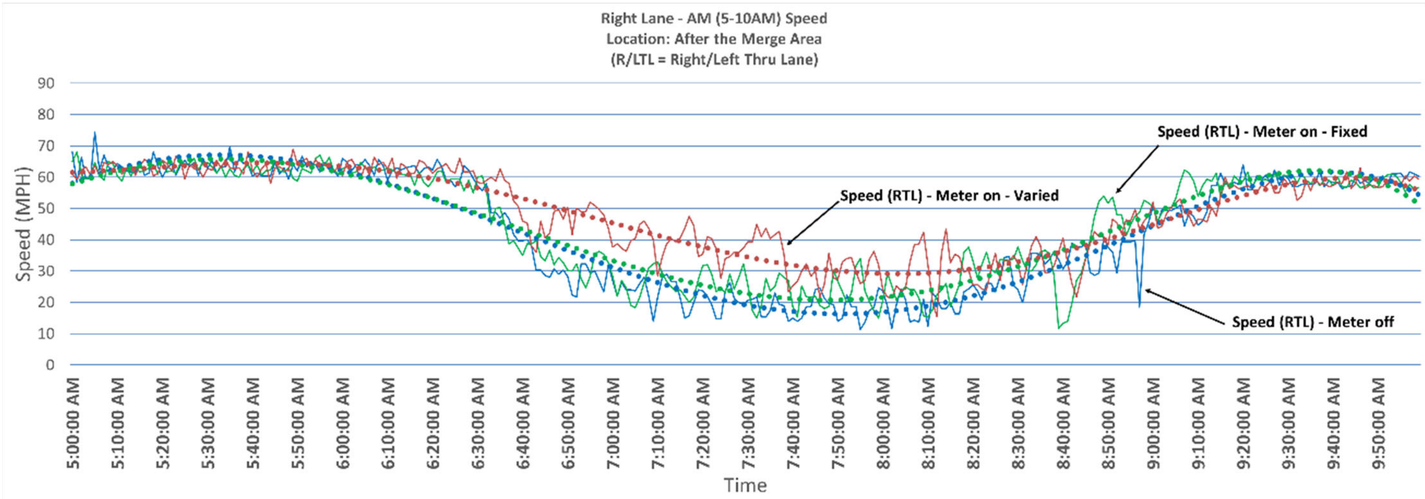
Table 29. Speed comparison, meter-off scenario and variable-cycle length ramp metering (left lane).

Meter Off (Without Ramp Metering) and Option 2 (Variable-cycle Length)								
	07:30 to 07:45		07:45 to 08:00		08:00 to 08:15		08:15 to 08:30	
	Meter Off	Option 2	Meter Off	Option 2	Meter Off	Option 2	Meter Off	Option 2
Volume (vehicles/time period)	289	389	299	365	304	333	343	378
Mean Speed (mph)	17.49	38.60	18.42	33.56	18.87	32.00	26.69	33.33
85th Percentile (mph)	25.40	61.40	27.00	51.80	29.00	47.85	39.00	51.00
SD	8.29	21.49	7.93	14.26	8.51	15.08	11.91	13.54
Mean Speed t_{static}	**-6.15**		**-6.22**		**-4.96**		**-2.47**	

(Bold indicates significance at the 95% confidence level, X = .05.)

Similar to the mean speeds, the 85th percentile speeds on the mainline of the freeway also increased for all time periods from 7:30 to 8:30 a.m. The *t*-test results indicated the increases in mean speed during the variable-cycle length ramp metering scenario were also statistically significant for all time periods.

After implementing ramp metering, the speeds of vehicles on the mainline of the freeway increased in both scenarios (Figure 25). Therefore, it seems that implementing ramp metering had a positive effect and although the changes varied, the changes were found to be statistically significant.



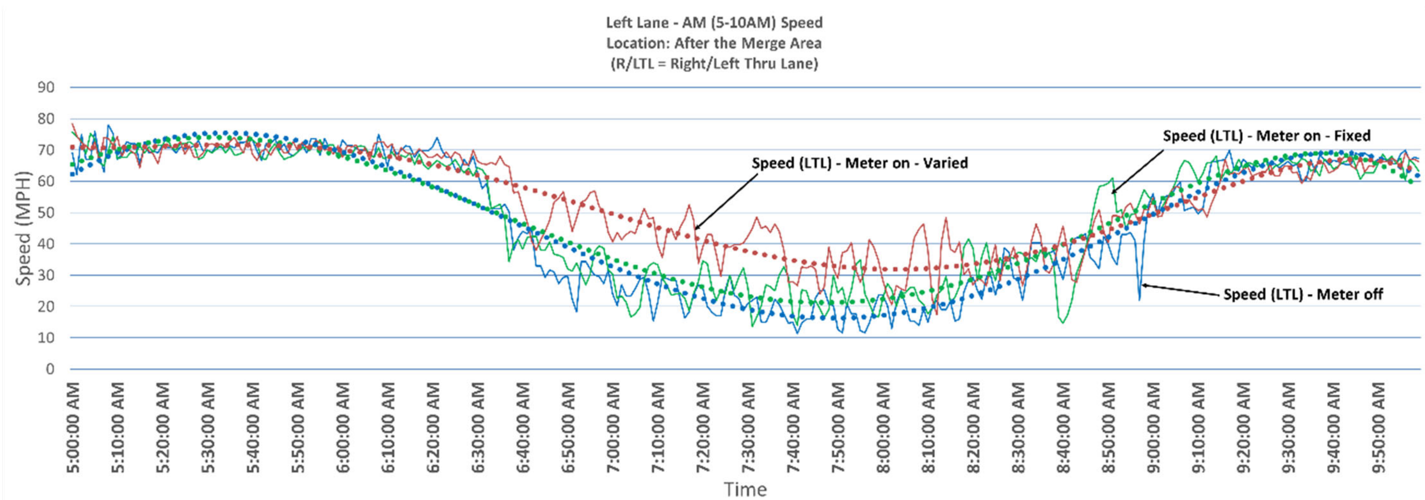


Figure 25. Vehicle speed—Location 3: After the merge area.

Overall, speeds increased in both right and left lanes, under the variable-cycle length ramp metering scenario by 57.2% (11.45 mph) and 69.8% (14.17 mph), respectively. The left lane was expected to see a larger increase. However, it is clear that when the ramp volume exceeds 650–750 vph and mainline volume reaches 1,600 vph, fixed-cycle length ramp metering scenario appears to perform better.

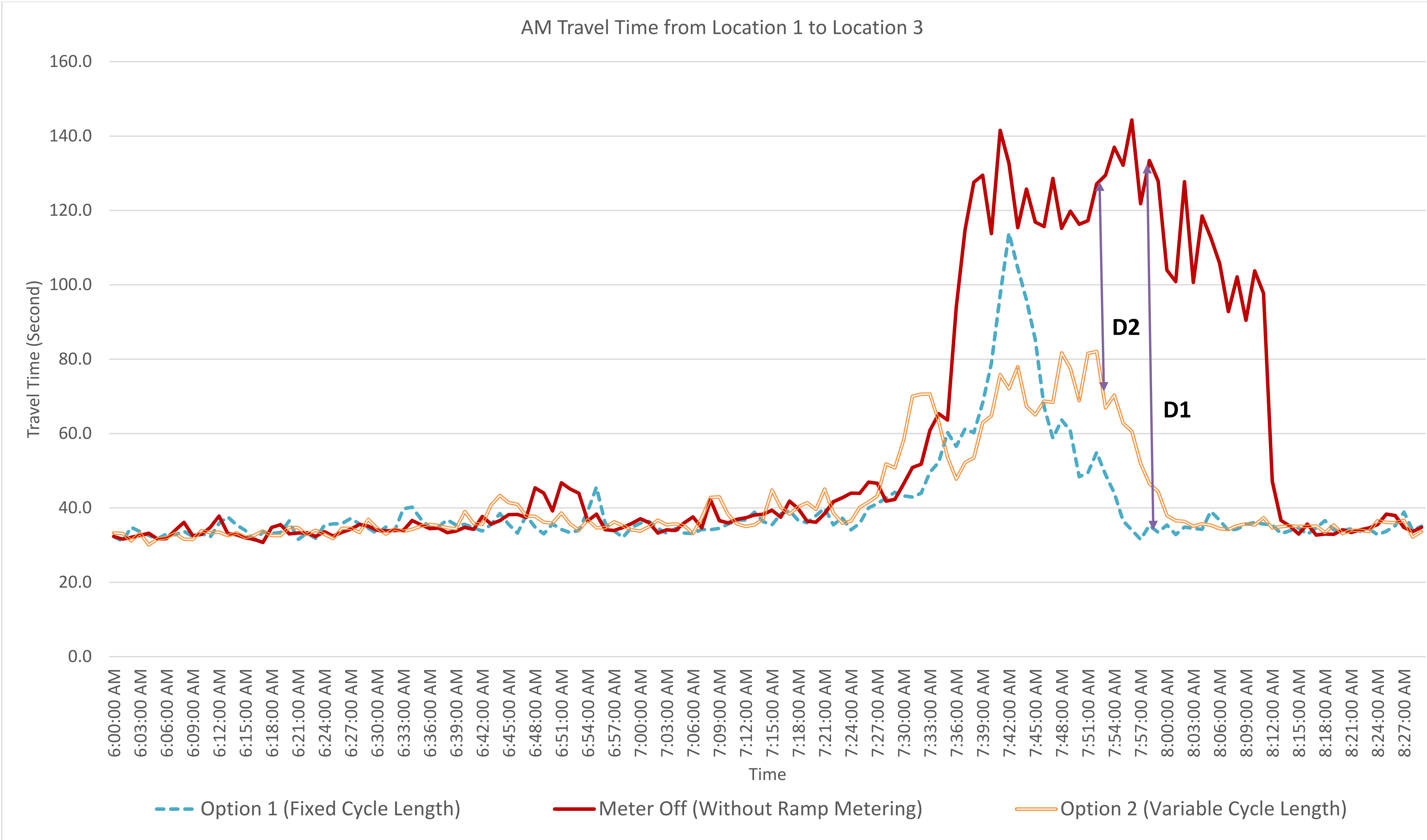
6.4. Comparison of Travel Time

The comparison of travel times through work zones is a good measurement of effectiveness to determine the effect of implementing ramp metering. In this study, the team used locations 1 and 3 (defined in Section 6.1) as the reference points to determine the travel time. Ramp metering controlled the number of vehicles released from the ramp to the mainline of the freeway and it is expected to have positive effects on vehicle merging near the ramp, which should result in shorter travel time on the mainline.

6.4.1 MN Route 52, Rochester, Minnesota

The team conducted an analysis of vehicle travel time of on the mainline of the freeway from Location 1 to Location 3 in the morning peak period (6:00 to 8:30 a.m.) to determine the effects of implementing ramp metering on both ramp-metering scenarios.

Figure 26 illustrates travel time from Location 1 to Location 3 at the different scenarios. It shows that meter-off scenario had a longer travel time than both Meter-on scenarios during the a.m. peak hour period.



D1: Variation Between Meter Off and Option 1
D2: Variation Between Meter Off and Option 2

Figure 26. A.M. peak hour travel time from Location 1 to Location 3 (distance: 2,800 ft)

The team used a comparison of travel times to evaluate the effect of ramp metering and determine if ramp metering caused changes in travel characteristics. The team used the *t*-statistic to evaluate the effect of different ramp-metering scenarios. The team calculated changes in the average travel time and the 85th percentile travel time for vehicles traveling from Location 1 to Location 3 between the *with* and *without* ramp metering scenarios. Tables 28 and 29 show the comparison of average travel time, the 85th percentile travel time, and the statistical test results *with* and *without* ramp metering.

6.4.1.1 Meter-off Scenario vs. Fixed-cycle Length Ramp Metering

As Table 30 shows, the average travel time from Location 1 to Location 3 decreased for all time periods before 8:15 a.m. Travel time savings per vehicle ranged from 28% in the early stages of the ramp metering being turned on to over 60% when fully regulating traffic flows.

Table 30. Travel time comparison, meter-off scenario and fixed-cycle length ramp metering.

Meter off (Without Ramp Metering) and Option 1 (Fixed-cycle Length)								
	07:30 to 07:45		07:45 to 08:00		08:00 to 08:15		08:15 to 08:30	
	Meter off	Option 1	Meter off	Option 1	Meter off	Option 1	Meter off	Option 1
Volume (vehicles/time period)	450	471	418	436	403	360	342	332
Average Travel Time/vehicle (seconds)	95.60	68.62	125.53	50.15	91.73	35.05	34.57	34.60
85th Percentile Travel Time (seconds)	129.29	97.11	133.30	63.36	111.98	36.06	35.66	35.23
SD	34.98	23.74	8.88	15.24	28.63	1.55	1.73	1.51
Mean Speed t_{static}	**2.47**		**16.55**		**7.66**		-0.06	

Similarly, the 85th percentile travel time from Location 1 to Location 3 also decreased for all time periods from 7:30 to 8:30 a.m. Overall, the average travel time per vehicle was reduced from 88.2 seconds to 49.0 seconds per vehicle (44.7% decrease). The *t*-test results indicated statistically significant decreases in travel time during fixed-cycle length ramp-metering scenario.

6.4.1.2 Meter-off Scenario vs. Variable-cycle Length Ramp Metering

As Table 31 shows, the average travel time from location 1 to location 3 decreased for all time periods prior to 8:15 a.m. Travel time savings per vehicle were almost identical to Meter On (fixed time) and ranged from 33 percent in the early stages of the ramp metering being turned on to over 60 percent when fully regulating traffic flows.

Similar to the mean speeds, the 85^{th} percentile travel time from Location 1 to Location 3 also decreased for all time periods prior to 8:15 a.m. The *t*-test results indicated statistically significant decreases in travel time during variable-cycle length ramp metering scenario for the time periods from 7:30 to 8:15 a.m.

After implementing ramp metering, the travel time from Location 1 to Location 3 decreased in both ramp-metering scenarios. Overall, the average travel time per vehicle was reduced from 88.2 seconds to 52.3 seconds per vehicle (41% decrease).The travel time savings were similar and statistically significant. It can be reasonably concluded that the improved travel time (42%

reduction) is the result of implementing ramp metering. Therefore, there seems to be a positive effect on travel time associated with implementing ramp metering.

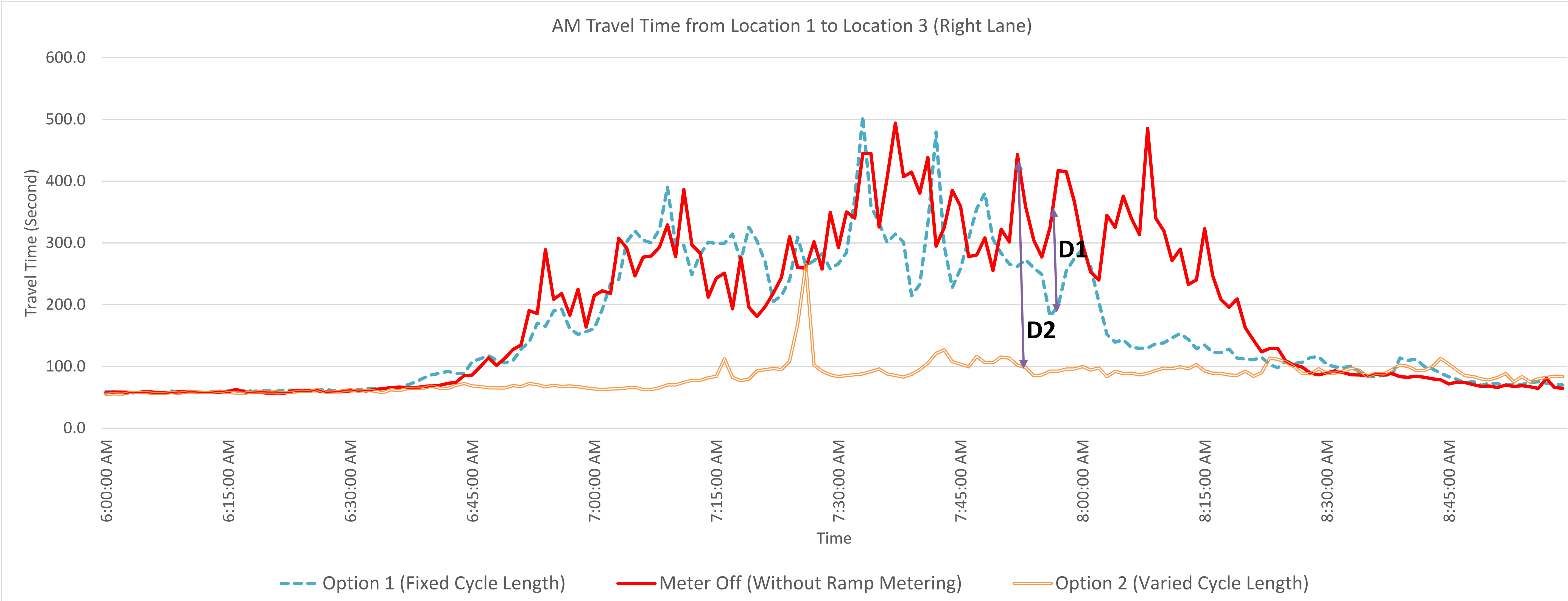
Table 31. Travel time comparison, meter-off scenario and variable-cycle length ramp metering.

Meter off (Without Ramp Metering) and Option 2 (Varied-cycle Length)								
	07:30 to 07:45		07:45 to 08:00		08:00 to 08:15		08:15 to 08:30	
	Meter off	Option 2	Meter off	Option 2	Meter off	Option 2	Meter off	Option 2
Volume (vehicles/time period)	450	454	418	439	403	367	342	308
Average Travel Time/vehicle (seconds)	95.60	64.03	125.53	66.50	91.73	35.62	34.57	34.66
85th Percentile Travel Time (seconds)	129.29	71.90	133.30	81.16	111.98	36.57	35.66	36.11
SD	34.98	9.22	8.88	11.95	28.63	1.05	1.73	1.36
Mean Speed t_{static}	**3.38**		**15.36**		**7.59**		-0.17	

6.4.2 I-279, Ohio Township, Pennsylvania

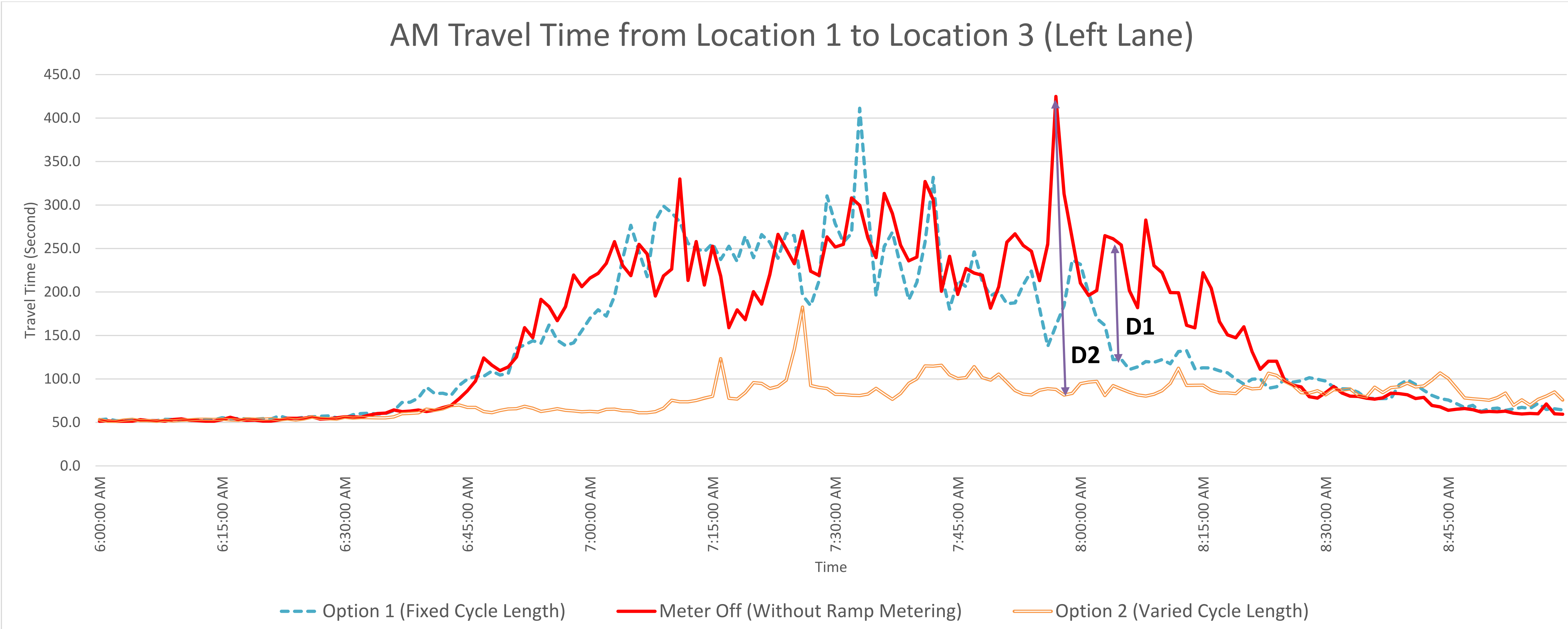
The team also conducted an analysis of travel time of vehicles on the mainline (both right and left lanes) of the freeway from Location 1 to Location 3 in the morning peak period (6:00 to 9:00 a.m.) to determine the effects of implementing ramp metering on both ramp-metering scenarios.

Figures 27 and 28 illustrate travel time from Location 1 to Location 3 at the different scenarios. It shows that meter-off scenario had a longer travel time than both Meter-on scenarios during the a.m. peak hour period for both right and left lanes.



D1: Variation Between Meter Off and Option 1
D2: Variation Between Meter Off and Option 2

Figure 27. A.M. peak hour travel time from Location 1 to Location 3, right lane (distance: 5,280 ft).



D1: Variation Between Meter Off and Option 1
D2: Variation Between Meter Off and Option 2

Figure 28. A.M. peak hour travel time from Location 1 to Location 3, left lane (distance: 5,280 ft).

The team used a comparison of travel times to evaluate the effect of ramp metering and determine if ramp metering caused changes in travel characteristics. The *t*-statistic was used to evaluate the effect of different ramp metering scenarios. The team calculated changes in average travel time and the 85th percentile travel time for vehicles traveling from Location 1 to Location 3 between the *with* and *without* ramp metering scenarios for both right lane and left lane. Tables 32 and 33 show the comparison of average travel time and the 85th percentile travel time along with the statistical test results *with* and *without* ramp metering.

6.4.2.1 Meter-off Scenario vs. Fixed-cycle Length Ramp Metering

As Tables 32 and 33 show, the average travel time from Location 1 to Location 3 decreased for all time periods from 7:30 to 8:30 a.m. for both right lane and left lane. Travel time savings per vehicle ranged from 16% in the early stages of the ramp metering being turned on to over 48% when fully regulating traffic flows for the right lane. For the left lane, travel time savings per vehicle ranged from 4% in the early stages of the ramp metering being turned on to more than 35% when fully regulating traffic flows for the right lane.

Table 32. Travel time comparison, meter-off scenario and fixed-cycle length ramp metering (right lane).

Meter off (Without Ramp Metering) and Option 1 (Fixed-cycle Length)								
	07:30 to 07:45		07:45 to 08:00		08:00 to 08:15		08:15 to 08:30	
	Meter off	Option 1	Meter off	Option 1	Meter off	Option 1	Meter off	Option 1
Volume (vehicles/time period)	200	255	190	240	195	245	252	266
Average Travel Time/vehicle (seconds)	383.03	321.11	334.17	273.92	311.25	161.79	156.96	113.99
85th Percentile Travel Time (seconds)	444.26	369.49	410.42	307.38	344.38	199.33	209.13	122.67
SD	60.19	83.16	57.31	50.97	65.22	50.09	67.54	9.78
Mean Speed t_{static}	**2.34**		**3.04**		**7.04**		**2.44**	

(Bold indicates significance at the 95% confidence level, α = .05.)

Table 33. Travel time comparison, meter-off scenario and fixed-cycle length ramp metering (left lane).

Meter off (Without Ramp Metering) and Option 1 (Fixed-cycle Length)								
	07:30 to 07:45		**07:45 to 08:00**		**08:00 to 08:15**		**08:15 to 08:30**	
	Meter off	**Option 1**	**Meter off**	**Option 1**	**Meter off**	**Option 1**	**Meter off**	**Option 1**
Volume (vehicles/time period)	289	379	299	262	304	353	343	378
Average Travel Time/vehicle (seconds)	268.28	256.77	249.59	198.74	215.04	139.07	131.51	100.75
85th Percentile Travel Time (seconds)	307.93	295.89	266.31	223.00	260.47	168.74	165.44	109.19
SD	36.49	59.71	58.62	27.82	37.17	35.83	43.62	7.10
Mean Speed t_{static}	0.64		**3.04**		**5.70**		**2.70**	

(Bold indicates significance at the 95% confidence level, $\alpha = .05$.)

Similarly, the 85th percentile travel time from Location 1 to Location 3 also decreased for all time periods from 7:30 to 8:30 a.m. for both right lane and left lane. Overall, travel time per vehicle was reduced from 287 seconds to 214.2 seconds per vehicle (25.4% decrease) and 209.6 seconds to 191.7 seconds (8.6% decrease) in the right lane and left lane, respectively. The *t*-test results indicated the decreases in travel time during fixed-cycle length ramp-metering scenario were statistically significant for all time periods from 7:30 to 8:30 a.m. for the right lane. The *t*-test results also indicated the decreases in travel time during fixed-cycle length ramp-metering scenario were statistically significant for time periods from 7:45 to 8:30 a.m. for the left lane.

6.4.2.2 Meter-off Scenario vs. Variable-cycle Length Ramp Metering

As Tables 34 and 35 show, the average travel time from Location 1 to Location 3 decreased for all time periods from 7:30 to 8:30 a.m. for both right lane and left lane. Travel time savings per vehicle ranged from 40% to 75% for the right lane. For the left lane, travel time savings per vehicle ranged from 31% to 65%.

Table 34. Travel time comparison, meter-off scenario and variable-cycle length ramp metering (right lane).

Meter off (Without Ramp Metering) and Option 2 (Variable-cycle Length)								
	07:30 to 07:45		07:45 to 08:00		08:00 to 08:15		08:15 to 08:30	
	Meter off	Option 2	Meter off	Option 2	Meter off	Option 2	Meter off	Option 2
Volume (vehicles/time period)	200	293	190	287	195	255	252	297
Average Travel Time/vehicle (seconds)	383.03	95.32	334.17	100.54	311.25	93.66	156.96	94.16
85th Percentile Travel Time (seconds)	444.26	107.45	410.42	112.63	344.38	99.23	209.13	106.17
SD	60.19	13.80	57.31	9.78	65.22	5.54	67.54	9.52
Mean Speed t_{static}	**18.05**		**15.56**		**12.87**		**3.57**	

(Bold indicates significance at the 95% confidence level, α = .05.)

Table 35. Travel time comparison, meter-off scenario and variable-cycle length ramp metering (left lane).

Meter off (Without Ramp Metering) and Option 2 (Variable-cycle Length)								
	07:30 to 07:45		07:45 to 08:00		08:00 to 08:15		08:15 to 08:30	
	Meter off	Option 2	Meter off	Option 2	Meter off	Option 2	Meter off	Option 2
Volume (vehicles/time period)	289	389	299	365	304	333	343	378
Average Travel Time/vehicle (seconds)	268.28	92.42	249.59	93.18	215.04	90.52	131.51	90.30
85th Percentile Travel Time (seconds)	307.93	113.75	266.31	101.58	260.47	96.24	165.44	96.75
SD	36.49	14.05	58.62	10.10	37.17	8.42	43.62	7.36
Mean Speed t_{static}	**17.42**		**10.18**		**12.66**		**3.61**	

(Bold indicates significance at the 95% confidence level, α = .05.)

Similar to the mean speeds, the 85th percentile travel time from Location 1 to Location 3 also decreased for all time periods from 7:30 to 8:30 a.m. for both right lane and left lane. Overall, travel time per vehicle was reduced from 287 seconds to 96 seconds (66.5% decrease) and 209.7 seconds to 90.9 seconds (56.6% decrease) in the right lane and left lane, respectively. The *t*-test results indicated the decreases in travel time during variable-cycle length ramp-metering scenario were statistically significant for all time periods from 7:30 to 8:30 a.m. for both right lane and left lane.

After implementing ramp metering, the travel time from Location 1 to Location 3 decreased in both ramp metering scenarios. The travel time savings were similar and statistically significant.

It can be reasonably concluded that the improved travel time (20% for fixed and 60% for variable) is the result of implementing ramp metering. Therefore, there seems to be a positive effect on travel time associated with implementing ramp metering. Variable-cycle length ramp-metering scenario seems to have a greater benefit when the network is not operating at saturation.

6.5. Comparison of Results for Frequency of Headway

Headway is a good measure of congestion and lack of passing opportunities created by the traffic mix; it is also a good measure of safety as lane changing and frequent passing generally lead to conflicts and the likelihood of crashes. In general, a longer headway accepted by a merging vehicle is safer than a shorter headway.

The team examined the headways accepted by following vehicles to see if there were any differences between the *with* and *without* implementation of ramp metering.

6.5.1 MN Route 52, Rochester, Minnesota

The team conducted an analysis of headways of vehicles on the mainline of the freeway at Location 3 in the morning peak hour (7:30 to 8:30 a.m.) to determine the average values and distribution for both ramp-metering scenarios.

As mentioned earlier, the team used the K-S test to judge how faithfully a distribution fits the sample data. The K-S test was adopted to determine the goodness-of-fit in the work zone traffic condition.

Table 36. K-S test results for the meter-on scenarios.

	Scenarios		
	Meter Off	Meter On (Fixed-cycle Length)	Meter-On (Variable-cycle Length)
Volume (Vehicle/Hour)	1614	1600	1568
Mean Headway (seconds)	2.29	2.42	2.44
Median Headway (seconds)	2.17	2.25	2.23
Maximum Difference (*D*)		0.167	0.183
Significant Difference		No	No

Table 36 summarizes the K-S test results of the meter-on scenarios. The following section discusses both Meter-on scenarios.

6.5.1.2 Meter-off Scenario vs. Fixed-cycle Length Ramp Metering

Figure 29 presents a visual performance comparison of headway distributions through a cumulative distribution function in the morning peak period at Location 3 for the meter-Off scenario and the fixed-cycle length ramp metering. The team observed a slight shift in the headway distribution toward longer headways resulting from ramp metering. The Meter-on scenario had a longer headway in approximately 50% of samples (cumulative percentage 45% to 95%) with a maximum headway difference of 0.4 seconds. The mean value of headway was 2.42 seconds *with* ramp metering as opposed to 2.29 seconds *without* ramp metering. With the significance level α of 0.05, the critical statistic of K-S test for the maximum difference between the cumulative distributions, D, was 0.25. The results of the K-S test for (meter-off scenario vs. fixed-cycle length ramp metering) shows a value of D of 0.167 (less than the critical value of 0.25), which suggests the differences in the two cumulative distributions are not statistically significant.

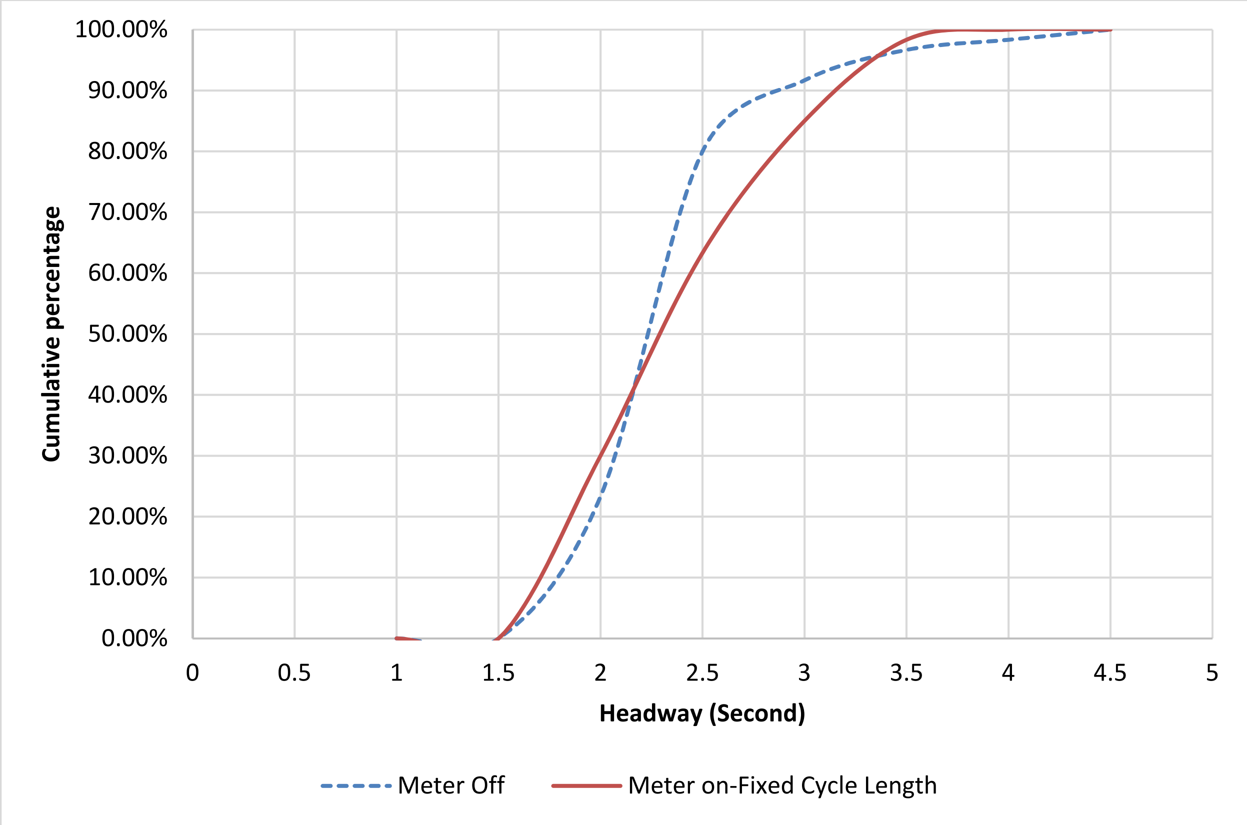


Figure 29. Cumulative headway distribution plot, meter-off scenario vs. fixed-cycle length ramp metering (7:30 to 8:30 a.m.).

6.5.1.3 Meter-off Scenario vs. Variable-cycle Length Ramp Metering

Figure 30 presents a visual performance comparison of headway distributions through a cumulative distribution function in the morning peak period at Location 3 for the meter-off scenario and variable-cycle length ramp metering. The team observed a slight shift in the headway distribution toward longer headways as a result of ramp metering. The meter-on scenario has a longer headway in more than 90% of the samples (cumulative percentage 5% to 97%) with a maximum headway difference of 0.4 sec. The mean value of headway was 2.44 seconds with ramp metering as opposed to 2.29 seconds without ramp metering. With the significance level α of 0.05, the critical statistic of K-S test for the maximum difference between the cumulative distributions, D, was 0.25. The results of the K-S test for (meter-off scenario vs. variable-cycle length ramp metering) shows a value of D of 0.183 (less than the critical value of 0.25), which suggests the differences in the two cumulative distributions are not statistically significant.

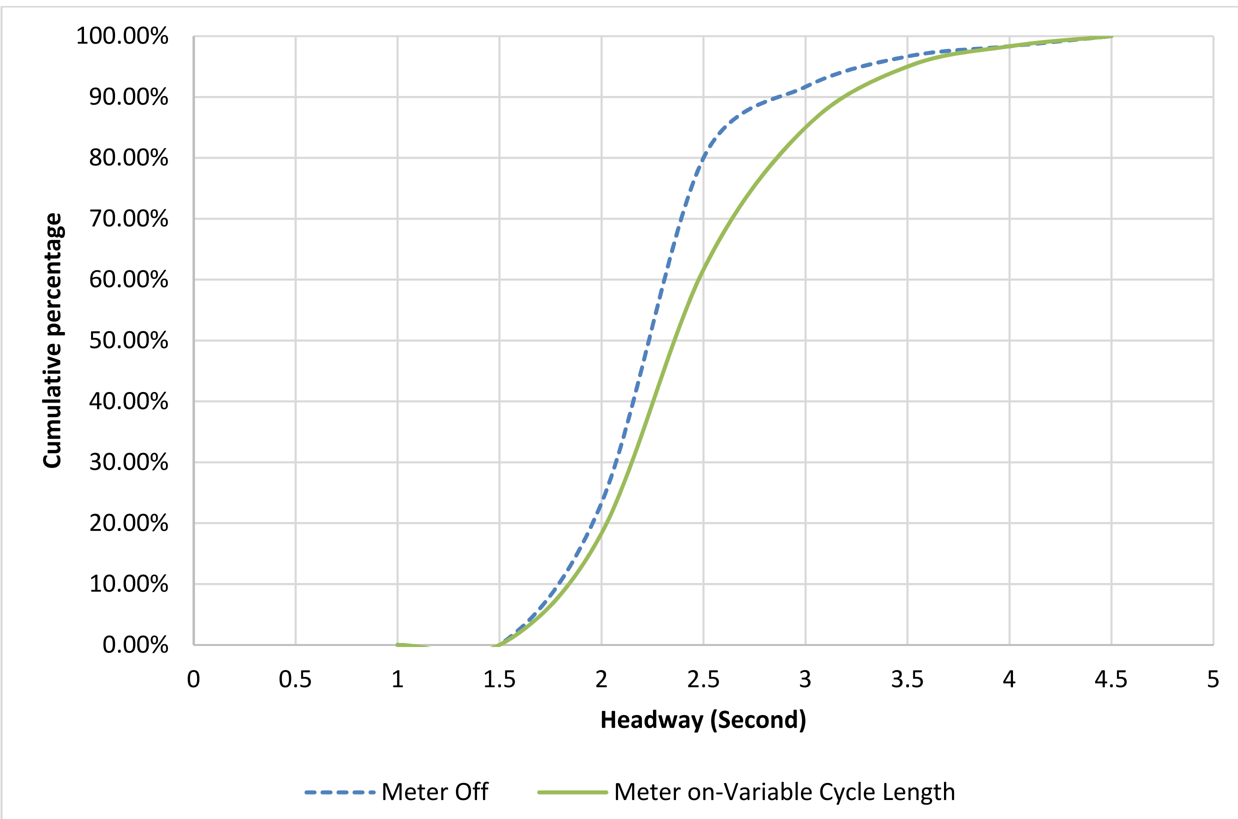


Figure 30. Cumulative headway distribution plot, meter-off scenario vs. variable-cycle length ramp metering (7:30 to 8:30 a.m.).

The headways of vehicles on the mainline of the freeway at Location 3 showed an increase in both ramp-metering scenarios from meter-off scenario (*without* ramp metering). The result of the K-S test indicated that the differences in the two cumulative distributions were not statistically significant. It can be reasonably concluded that although the headway increased slightly, a positive effect, this was not as a result of implementing ramp metering. The converse is that by implementing ramp metering, the headway remains unchanged, and assuming that headway is a safety surrogate, then safety remained unchanged.

6.5.2 I-279, Ohio Township, Pennsylvania

The team conducted an analysis of headways of vehicles on the mainline (both right lane and left lane) of the freeway at Location 3 in the morning peak hour (7:30 to 8:30 a.m.) to determine the average values and distribution for both ramp metering scenarios.

As noted, above, the team used the K-S test to judge how faithfully a distribution fits the sample data. The K-S test was adopted to determine the goodness-of-fit in the work zone traffic condition.

6.5.2.1 Right Lane

Table 37 summarizes the K-S test results of the meter-on scenarios for the right lane. The following section discusses both meter-on scenarios.

Table 37. K-S test results for the meter-on scenarios (right lane).

Right Lane	Scenarios		
	Meter Off	Meter On (Fixed-cycle Length)	Meter On (Varied-cycle Length)
Volume (Vehicle/Hour)	837	1005	1,133
Mean Headway (seconds)	4.01	3.74	3.22
Median Headway (seconds)	3.75	3.53	2.86
Maximum Difference (*D*)		0.10	0.28
Significance		No	Yes

Meter-off Scenario vs. Fixed-cycle Length Ramp Metering (Right Lane)

Figure 31 presents a comparison of cumulative headway distributions in the morning peak period at Location 3 for meter-off scenario and fixed-cycle length ramp metering. The team observed a shift in the headway distribution toward shorter headway resulting from ramp metering. The mean value of headway was 3.74 seconds *with* ramp metering as opposed to 4.01 seconds *without* ramp metering. With the significance level α of 0.05, the critical statistic of K-S test for the maximum difference between the cumulative distributions, *D*, is 0.16. The results of the K-S test (meter-off scenario vs. fixed-cycle length ramp metering) shows a value of D of 0.10 (less than the critical value of 0.16), which suggests the differences in the two cumulative distributions are not statistically significant.

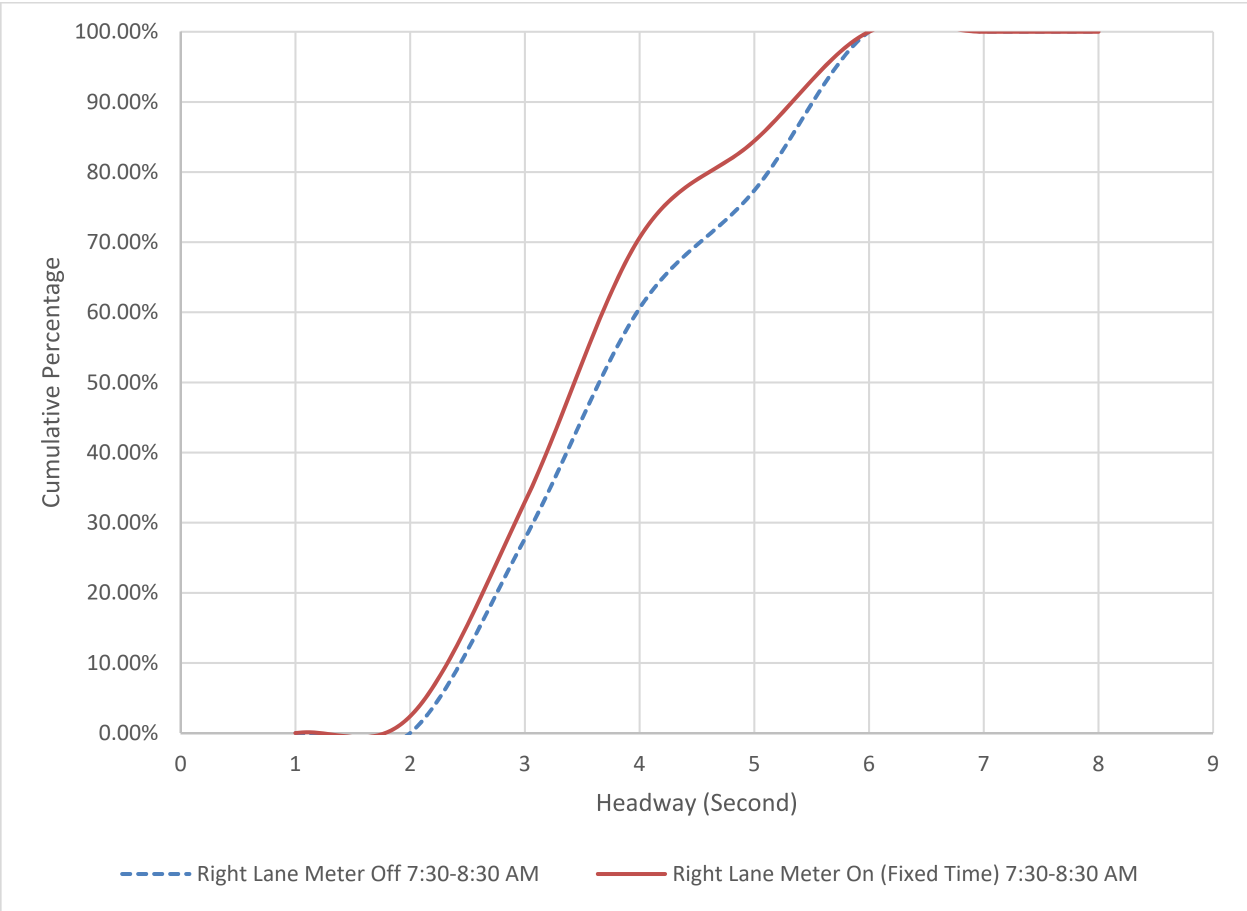


Figure 31. Cumulative headway distribution plot, meter-off scenario vs. fixed-cycle length ramp metering, right lane (7:30 to 8:30 a.m.).

Meter-off Scenario vs. Variable-cycle Length Ramp Metering (Right Lane)

Figure 32 presents a visual performance comparison of headway distributions through a cumulative distribution function in the morning peak period at Location 3 for meter-off scenario and variable-cycle length ramp metering. The team observed a shift in the headway distribution toward shorter headway as a result of ramp metering. The mean value of headway was 3.22 seconds with ramp metering as opposed to 4.01 seconds without ramp metering. With the significance level α of 0.05, the critical statistic of the K-S test for the maximum difference between the cumulative distributions, D, is 0.16. The results of the K-S test (meter-off scenario vs. variable-cycle length ramp metering) shows a value of D of 0.28 (greater than the critical value of 0.16), which suggests the differences in the two cumulative distributions are statistically significant.

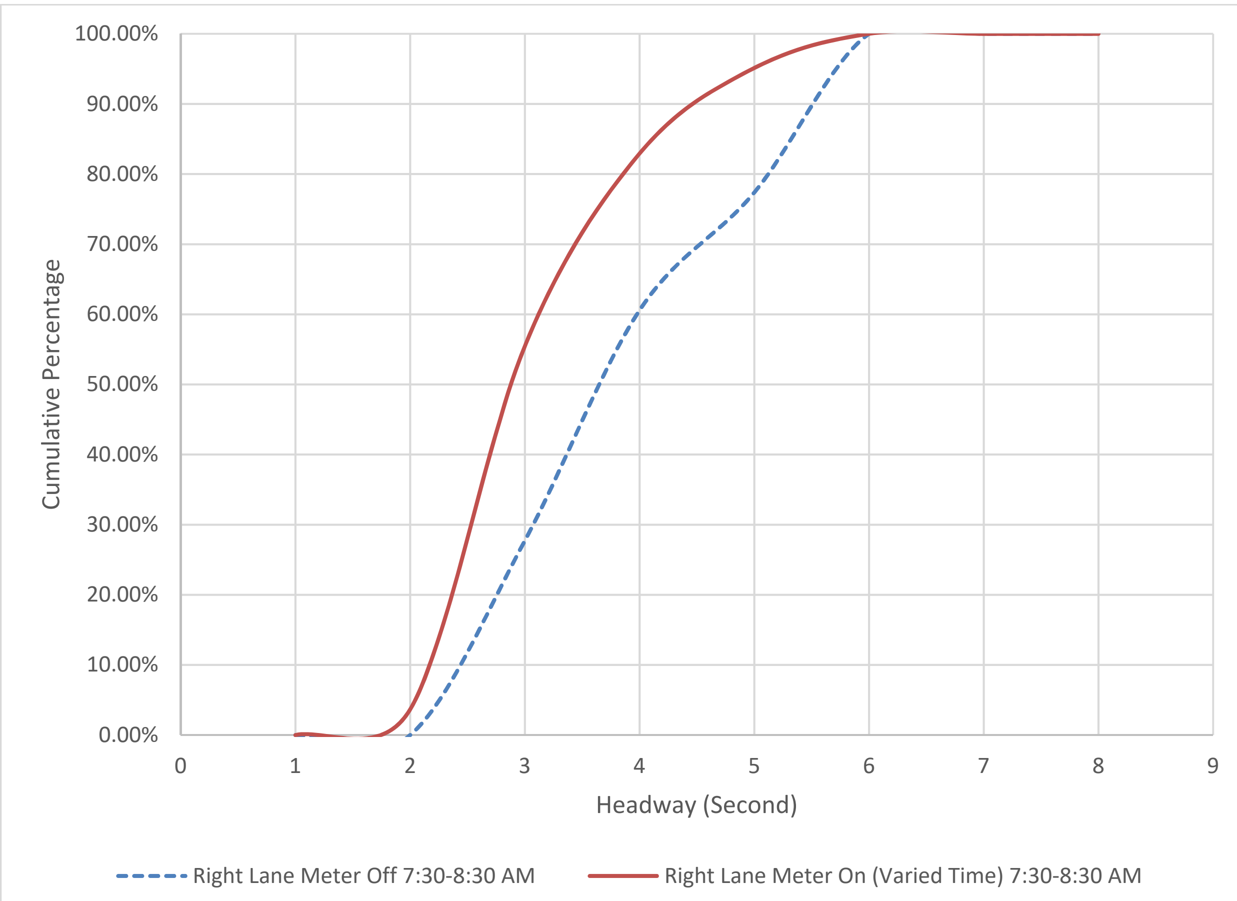


Figure 32. Cumulative headway distribution plot, meter-off scenario vs. variable-cycle length ramp metering, right lane (7:30–8:30 a.m.).

6.5.2.2 Left Lane

Table 38 summarizes the K-S test results of the meter-on scenarios for the left lane. The following discusses both Meter-on scenarios.

Table 38. K-S test results for the meter-on scenarios (left lane).

Left Lane	Scenarios		
	Meter Off	Meter On (Fixed-cycle Length)	Meter On (Varied-cycle Length)
Volume (Vehicle/Hour)	1235	1472	1465
Mean Headway (seconds)	3.24	2.66	2.62
Median Headway (seconds)	2.86	2.40	2.40
Maximum Difference (*D*)		0.22	0.24
Significance		Yes	Yes

Meter-off Scenario vs. Fixed-cycle Length Ramp Metering (Left Lane)

Figure 33 presents a visual performance comparison of headway distributions through a cumulative distribution function in the morning peak period at Location 3 for the meter-off scenario and fixed-cycle length ramp metering. The team observed a shift in the headway distribution toward shorter headway resulting from ramp metering. The mean value of headway was 2.66 seconds with ramp metering as opposed to 3.24 seconds without ramp metering. With the significance level α of 0.05, the critical statistic of the K-S test for the maximum difference between the cumulative distributions, D, was 0.15. The results of K-S test (meter-off scenario vs. fixed-cycle length ramp metering) shows a value of D of 0.22 (greater than the critical value of 0.15), which suggests the differences in the two cumulative distributions are statistically significant.

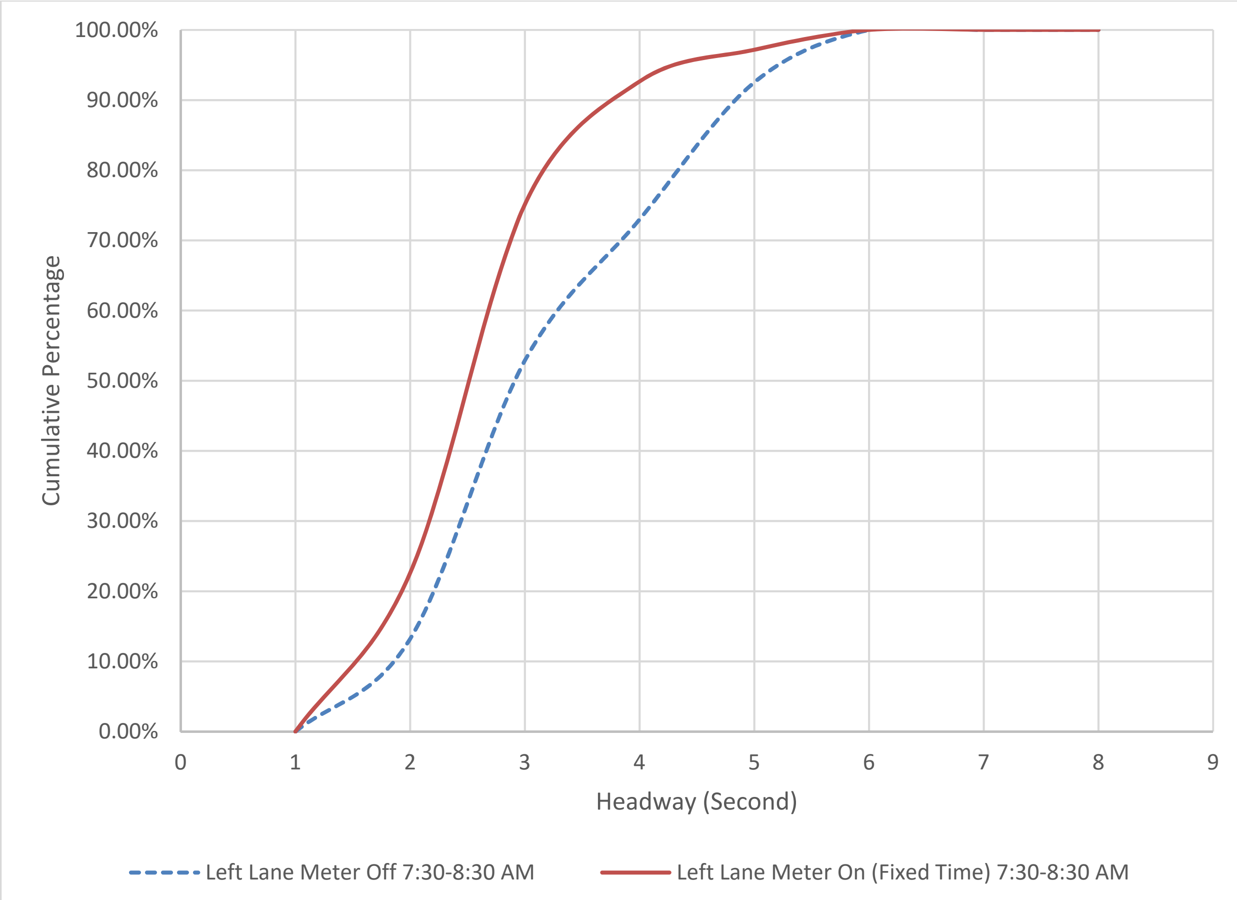


Figure 33. Cumulative headway distribution plot, meter-off scenario vs. fixed-cycle length ramp metering, left lane (7:30 to 8:30 a.m.).

Meter-off Scenario vs. Variable-cycle Length Ramp Metering (Left Lane)

Figure 34 presents a visual performance comparison of headway distributions through a cumulative distribution function in the morning peak period at location 3 for the meter-off scenario and variable-cycle length ramp metering. The team observed a shift in the headway distribution toward shorter headway as a result of ramp metering. The mean value of headway was 2.62 seconds with ramp metering as opposed to 3.24 seconds without ramp metering. With the significance level α of 0.05, the critical statistic of the K-S test for the maximum difference between the cumulative distributions, D, was 0.15. The results of the K-S test for (meter-off scenario vs. variable-cycle length ramp metering) shows a value of D of 0.24 (greater than the critical value of 0.15), which suggests the differences in the two cumulative distributions are statistically significant.

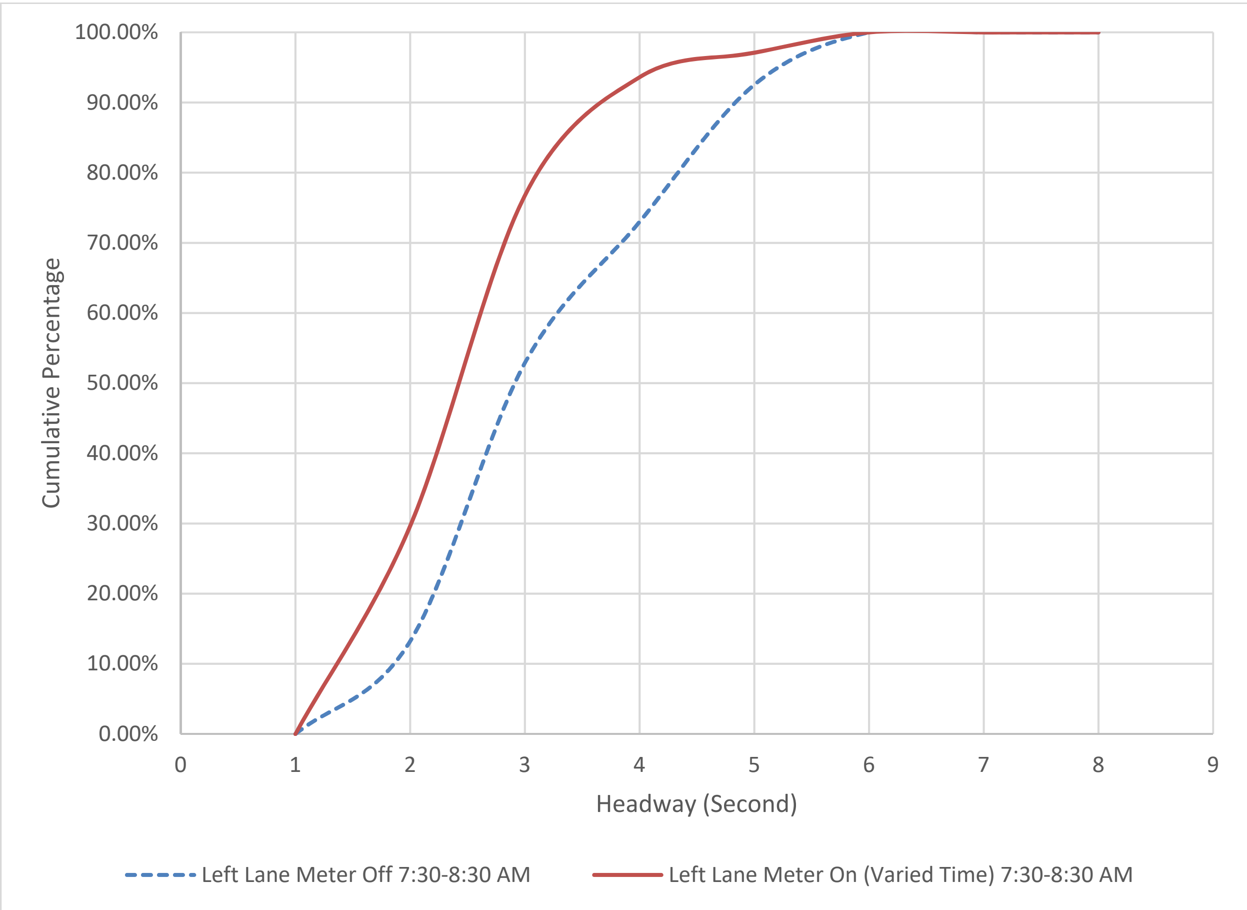
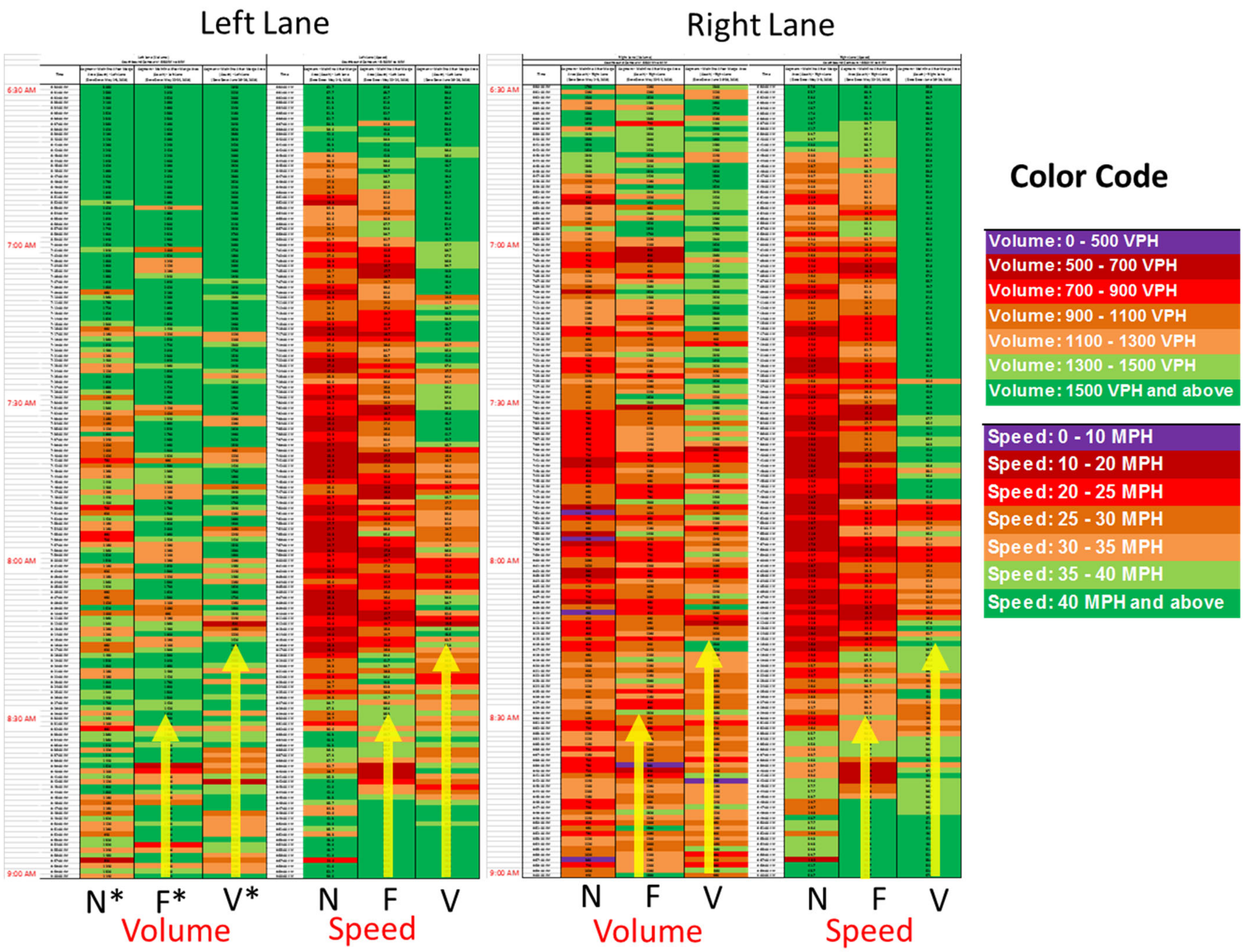


Figure 34. Cumulative headway distribution plot, meter-off scenario vs. variable-cycle length ramp metering, left lane (7:30–8:30 a.m.).

The headways of vehicles on the mainline of the freeway at Location 3 exhibited a decrease in both ramp metering scenarios from the meter-off scenario (without ramp metering). The result of the K-S test indicated that the differences in the two cumulative distributions were statistically significant for three scenario comparisons (right lane, meter-off vs. variable-cycle length; left lane, meter-off vs. fixed-cycle length; left lane, meter-off vs. variable-cycle length) and not statistically significant for one scenario-comparison (right lane, meter-off vs. fixed-cycle). It can be reasonably concluded that the decrease in headways, a negative effect, was the result of implementing ramp metering. However, this can be expected as the mainline traffic volumes increased as ramp platoons were controlled.

6.6. Network Summary

Figure 35 provides a visual volume and speed graphic of the effect of ramp metering under meter off, fixed-cycle length, and variable-cycle length scenarios taken at the gore (mainline and ramp). It is clearly visible that traffic volumes increase in both left and right lanes as demonstrated by a greater concentration of lighter colors for both fixed-cycle and variable-cycle length scenarios. Similarly, the same observation can be demonstrated for vehicle speeds.



***N–meter-off scenario, F–fixed-cycle length scenario, V–variable-cycle length ramp metering**

Figure 35. Volume vs Speed charts (left/right lane) at gore.

Figure 36 illustrates the positive effect along the corridor *before/after* metering by operations. While both fixed-cycle length and variable-cycle length scenarios yielded positive results, the variable-cycle length scenario showed improved results with respect to vehicle speeds. All data collection segments (1 through 4) are shown in Figure 36 with location 1 and 4 being furthest upstream and downstream, respectively. A visual comparison of each segment under respective modes - meter off, fixed-cycle length, and variable-cycle length scenarios reveal less lower speed (greater concentration of lighter colors), respectively.

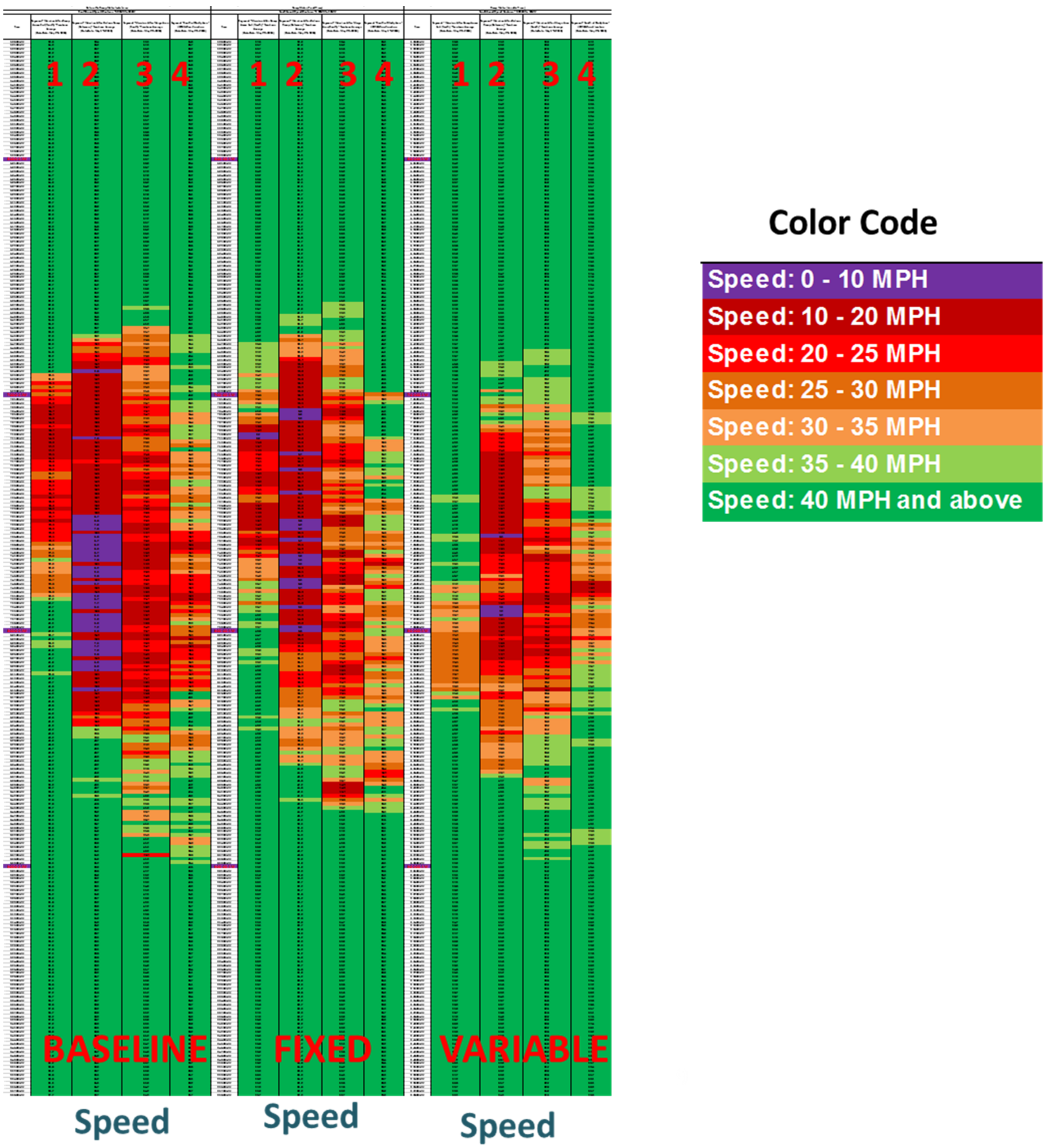


Figure 36. Network effect.

6.7. Driver Compliance Rates

The primary interest in evaluating the effectiveness of ramp metering is the drivers' compliance rate. The compliance rate will determine whether ramp metering works well for the study area.

6.7.1 MN Route 52, Rochester, Minnesota

The design of the freeway entrance ramp allows for the use of three-section heads (MUTCD 2009, Section 4I). Based on the observed ramp flows, the team developed two signalization schemes (1) Fixed-cycle length—green, yellow, and red times are consistent for each cycle. (2) Variable-cycle length—green, yellow, and red times vary based on traffic flow on the ramp.

The duration for green, yellow, and red times were set for 1.0, 0.5, and 3.5 seconds, respectively, for fixed-cycle length ramp metering. For variable-cycle length ramp metering, the green time varied from 1 to 1.5 seconds, the yellow time varied from 0.5 to 1.5 seconds, and the red time varied from 3.5 to 4.5 seconds. The team reviewed 1 hour of video on-ramp for both ramp metering scenarios during the a.m. peak hour and with no enforcement present. The following sample sizes and compliance rates were obtained for the ramp metering:

- Fixed-cycle length ramp metering—sample size: 445, 63.1% compliance.
- Variable-cycle length ramp metering—sample size: 376, 76.3% compliance.

6.7.2 I-279, Ohio Township, Pennsylvania

The team developed two signalization schemes (1) Fixed-cycle length—green and red times were consistent for each cycle. (2) Variable-cycle length—green and red times varied based on traffic flow on the ramp. The duration for green and red times were set for 0.5 and 3.5 seconds, respectively, for Fixed-cycle length ramp metering. For Variable-cycle length ramp metering, the red time varied from 3.5 to 5 seconds.

The team reviewed 1 hour of video on-ramp for both ramp-metering scenarios during the a.m. peak hour, with no enforcement present. The following sample sizes and compliance rates were obtained for the ramp metering:

- Fixed-cycle length ramp metering—sample size: 283, 92.2 percent compliance.
- Variable-cycle length ramp metering—sample size: 247, 93.5 percent compliance.

In general, driver compliance was greater than expected given that no enforcement was present prior to or during the study period. It appears that the two-signal head commands greater compliance than a three-signal head.

6.8. Work Zone Crash Modification Factor for Ramp Metering

This section discusses the CMF calculation for ramp metering in work zones. Table 39 shows the expected and actual crash results for the deployment of the ramp meter. The Total Hours column indicates the number of hours of data analyzed.

Table 39. Expected and actual crash results for ramp metering.

Treatment	Total Hours	Expected Crashes	Actual Crashes	Percent Change
Ramp Meter Deployment	5,880	8.2	7	-15

For the ramp meter condition, there was a 15 percent decrease from expected to actual crashes. In order to determine the proportional effects of the treatments on the numbers of crashes, an odds ratio analysis was undertaken according to the following equations:

$$CMF_D = \frac{TA_D TE_{ND} / TE_D TA_{ND}}{(1 + 1/TE_{ND} + 1/TE_D + 1/TA_{ND})}$$

$$SE(CMF_D) = \sqrt{\frac{CMF_D^2 \, (1/TA_D + 1/TE_{ND} + 1/TE_D + 1/TA_{ND})}{(1 + 1/TE_{ND} + 1/TE_D + 1/TA_{ND})}}$$

Where:

CMF_D = crash modification factor = proportional effect of a deployment on crashes:

TA_D = total actual crashes during a deployment (equal to 7 in this case);

TE_D = total expected crashes during a deployment (equal to 8.2 in this case);

TA_{ND} = total actual crashes when nothing was deployed (equal to 5 in this case);

TE_{ND} = total expected crashes when nothing was deployed (equal to 7.2 in this case); and

SD (CMF_D) = standard error.

Table 40 shows the results from the CMF calculation. The calculated CMF for the deployment of ramp meter is less than 1, indicating that this treatment had some effect on reducing the number of crashes, without taking standard error into account.

Table 40. CMF results for ramp meter.

Treatment	CMF_D	$SE(CMF_D)$	ADT
Ramp Meter Deployment	0.847	0.544	Up to 100,000 Vehicles

The CMF calculation was limited because of the few test sites. Agencies should use this only as a guide, monitor all work zones, and take appropriate action to mitigate any increase in crashes (i.e., severity and number).

7.0 Field Evaluation of Reversible Lanes

A reversible lane is one in which the direction of traffic flow in one or more lanes is changed to the opposite direction for some period of time. Its utility is derived by taking advantage of the unused capacity of the minor flow direction to increase capacity in the major flow direction, thereby negating the need to construct additional lanes. Reversible lanes are particularly useful in work zones with a directional imbalance in excess of 65%–35% during weekday rush hours, where the existing number of lanes are reduced and the cost to provide additional capacity would be high and, perhaps, not possible because of the cost of ROW or other limitations. A concrete barrier, drums, or other traffic control devices separate the reversible lane from other lanes. Concrete barriers are generally used for longer work zones, which means there is no potential for diversions to on and off ramps and almost no access to or from the work zone area.

The primary benefit of reversible lane operation is reducing congestion during periods of high and unbalanced directional travel demand. However, only a few studies have attempted to determine the effects of reversible lanes in work zones of the unused capacity in the minor traffic direction. The goal of this study was to evaluate the operational and safety effectiveness of reversible lanes in work zones.

7.1. Site Selection and Characteristics

Through contacts made with state transportation agencies, the team identified the following three locations—two in Michigan and one in Minnesota—as test sites for evaluation:

- I-75 from Dixie Highway to Hess Road, Saginaw County, Michigan. Reversible-lane changeover in place during the weekend and mid-week to accommodate recreational and holiday traffic.
- I-94 between East 7th Street in St. Paul and Hwy 120/Century Ave. in Maplewood, Minnesota. Reversible-lane changeover in place after the morning peak period to accommodate the afternoon commuting traffic.
- I-75 and I-675 in Zilwaukee, Kochville, and Frankenlust Townships, Saginaw and Bay Counties, Michigan. Reversible-lane changeover in place during the weekend and mid-week to accommodate recreational and holiday traffic.

7.1.1 I-75, Saginaw County, Michigan

This project included 3.75 mi of pavement reconstruction with widening for additional lanes, bridge replacements, drainage improvements, and construction of a noise barrier wall on I-75 from Dixie Highway to Hess Road, Saginaw County.

The bridge replacements and road reconstruction started in March 2015, and ended in November 2016. The team collected data from June 28 to July 12, 2016, when average daily traffic peaked because of the holiday period. Average daily traffic ranged from 65,000 to 75,000 vehicles; however, during holiday periods the traffic ranged from 100,000 to 110,000 vehicles, an increase of over 50% in any direction with a 70%–30% direction split. *This was considered the most severe test of a reversible-lane operation.* Three lanes typically serviced each direction; however, during the work zone operation five lanes served both northbound and southbound, with one lane alternating based on daily traffic flow. Posted work zone speed limit was 60 mph. Table 41 shows an example of the reversible-lane changeover.

Table 41. I-75 Reversible-lane operational details.

Date	Day of Week	Number of SB lanes after Switch	Number of NB lanes after Switch	Time Switch Began
06/28/2016	Tuesday	2	3	10:00 a.m.
07/02/2016*	Saturday	2	3	8:00 a.m.
07/03/2016	Sunday	3	2	7:30 a.m.
07/06/2016	Wednesday	2	3	10:00 a.m.
07/09/2016	Saturday	3	2	10:00 a.m.
*Reversible-lane changeover was to occur on 07/02/16, but much higher holiday traffic volumes in the northbound direction necessitated a change to 07/03/16.				

7.1.2 I-94, Maplewood, Minnesota

The major part of this project was to resurface the pavement of EB and WB I-94 between Mounds Boulevard to east of Highway 120/Century Avenue. The total length of the project was approximately 5.5 mi. The project also included (1) constructing a new auxiliary lane and extend the existing auxiliary lane along EB I-94 between the exit to East 7th Street and the entrance from Mounds Boulevard, (2) constructing two emergency pull-off sites along EB I-94 between the exit to East 7th Street and the entrance from Mounds Boulevard, (3) resurfacing Highway 61 from north of Burns Avenue to Highway 5, (4) building a new noise wall and replacing part of an existing noise wall between Conway Street and Maple Street, and (5) repairing bridges.

The project started in spring 2016 and was completed in October 2018. The reversible lanes were in place during the time period from March to November 2017. The data were collected during the time period from June 24 to July 12, 2016. Average daily traffic ranged from 80,000 to 90,000 vehicles, with a 50%/50% direction split. Typically, three lanes serviced each direction. However, during the work zone operation, five lanes served both WB and EB, with one lane alternating based on peak period (a.m./p.m.) traffic flow. The changeover of the reversible lane occurred daily—morning peak period to afternoon peak period between noon and 2:00 p.m., with the other changeover occurring after 8:.00 p.m. for the next day's morning peak period. The posted speed limit was 45 mph. Figure 37 shows the cross-section for p.m. peak hour.

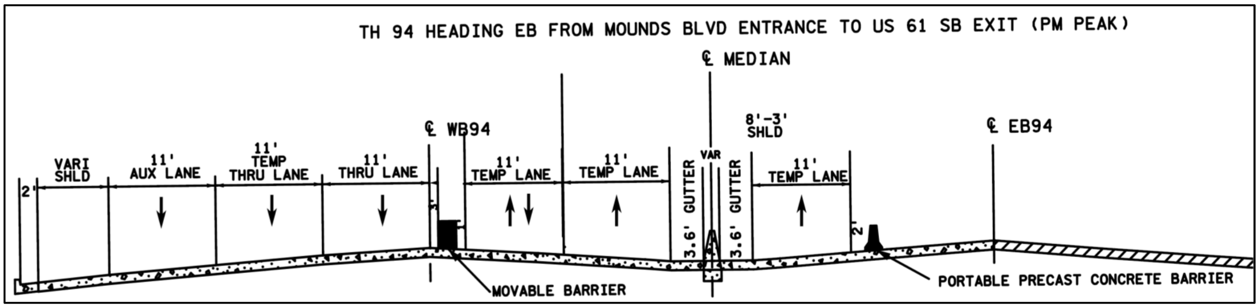


Figure 37. I-94 cross-section for p.m. peak hour.

7.1.3 I-75 and I-675, Saginaw and Bay Counties, Michigan

The MDOT invested $22.9 million to reconstruct 1 mi of I-75 and I-675 through Saginaw County. The I-75 work zone was located between Exit 154 (Adams Street) to south of Exit 160 (Saginaw Road). The I-675 work zone extended from I-75 in Zilwaukee to Exit 6 (Tittabawassee Road). Work included repairing and reconstructing multiple bridges and ramps and resurfacing with both concrete and asphalt.

Project construction started in March 2017 and was completed in November 2017, with the reversible lanes in place from June to October 2017. The team collected data during the time period from June 22 to July 13, 2017. ADT ranged from 65,000 to 75,000 vehicles; however, during holiday periods, the traffic ranged from 100,000 to 105,000 vehicles, an increase of over 50% in any direction with a 70%–30% direction split. *Similar to the prior I-75 (Saginaw) evaluation, this project was considered to be one of the most severe tests of a reversible-lane operation.* Typically, three lanes serviced each direction; however, during the work zone operation, five lanes served both northbound and southbound, with one lane alternating based on daily traffic flow. Posted speed limit was 60 mph. Table 42 shows an example of the reversible-lane changeover.

Table 42. I-75 and I-675 Reversible-lane operational details.

Date	Day of Week	Number of SB lanes after Switch	Number of NB lanes after Switch	Time Switch Began
6/24/2017	Saturday	3	2	2:15 a.m.
6/28/2017	Wednesday	2	3	11:30 a.m.
7/2/2017	Sunday	3	2	2:40 p.m.
7/6/2017	Thursday	2	3	8:00 a.m.

7/8/2017	Saturday	3	2	11:00 a.m.
7/12/2017	Wednesday	2	3	10:30 a.m.

7.2. Study Methodology

7.2.1 Data Collection Duration

I-75, Saginaw County, Michigan. Data were collected in March and in June/July 2016.

I-94, Maplewood, Minnesota. Data were collected in May and June 2017.

I-75 and I-675, Saginaw and Bay Counties, Michigan. Data were collected in June and July 2017.

7.2.2 Data Collection Procedures

The team used Wavetronix sensors to collect vehicular data. Wavetronix sensors collect data by emitting a microwave radar beam. The trailer-mounted sensors were stationed perpendicular to the roadway, outside the clear zone; as vehicles pass through the beam, the sensor detects the reflected microwave beam. The sensors can detect volume, vehicle classification, speed, 85th percentile speeds, and vehicle gaps across multiple lanes (up to 200 ft).

The team collected all vehicular data by direction and by lane. At each location, the team measured the following data per lane—volume, speed, vehicle classification, headway, and gap. The data were collected in 1-minute bins. All raw data were screened to exclude missing data values and outliers such as vehicles traveling at very low or very high speeds.

7.2.3 Measures of Effectiveness

The team evaluated the following operational MOEs:

- **Vehicle speed statistics along mainline *with* and *without* implementation of the reversible lane**. Because the reversible lane would maintain the capacity for the peak direction, this treatment should maintain vehicle operating speeds.
- **Travel time through the work zone *with* and *without* implementing the reversible lane.** Travel time through the work zone is a measurement used to determine the effect of implementing the reversible lane. For all sites, the team used the baseline location and work zone location as the reference points to determine the travel time. As stated previously, because the intent of the reversible lane was to maintain the capacity in the peak direction, this treatment should maintain vehicle travel time through the corridor.
- **Merging headways *with* and *without* implementing the reversible lane.** Vehicle headway is a measure of the temporal space between two vehicles. As the average of vehicle headways is the reciprocal of flow rate, vehicle headways represent microscopic

measures of flow passing a point. To some extent, the minimum acceptable mean headway determines the roadway capacity.

7.2.4 Method for a Statistical Test for Vehicle Speeds

The method for the statistical test for vehicle speeds is the same as that described in Section 5.2.5.

7.2.5 Method for a Statistical Test for Travel Time through the Work Zone

The method for the statistical test for vehicle speeds is the same as that described in Section 6.2.5.

7.2.6 Method for a Statistical Test for Frequency of Headway

The method for the statistical test for vehicle speeds is the same as that described in Section 5.2.6.

7.3. Field Evaluation Results

The team compared the different MOEs (i.e., vehicle speed, travel time, and headway) to evaluate the effect of the reversible lane and determine if the reversible lane improved travel characteristics. As indicated in Section 7.1, the team selected three project sites to conduct the evaluation study. The following sections discuss the results of each measure of effectiveness.

7.3.1 Location: I-75, Saginaw County, Michigan

7.3.1.1 Comparison of Results for Vehicle Speeds

The team collected data at four locations on I-75—two within the work zone (in the reversible-lane configuration) and one each upstream and downstream (outside the work zone). Figure 38 illustrates the data collection locations.

Figure 39 illustrates the baseline traffic ADT volumes, as well as the volumes carried by the work zone in the reversible-lane configuration for both northbound and southbound directions. Traffic increased by over 30,000 vehicles during the 4th of July holiday period, showcasing the capability of a reversible lane to change on demand, as occurred on July 2, 2016. The reversible-lane switch was to occur on July 2 to the southbound direction; however, because of the higher northbound traffic volumes, the switch was delayed to July 3, 2016. Figure 40 illustrates the hourly traffic volume changes and the capability of the reversible lane to handle these higher volumes.

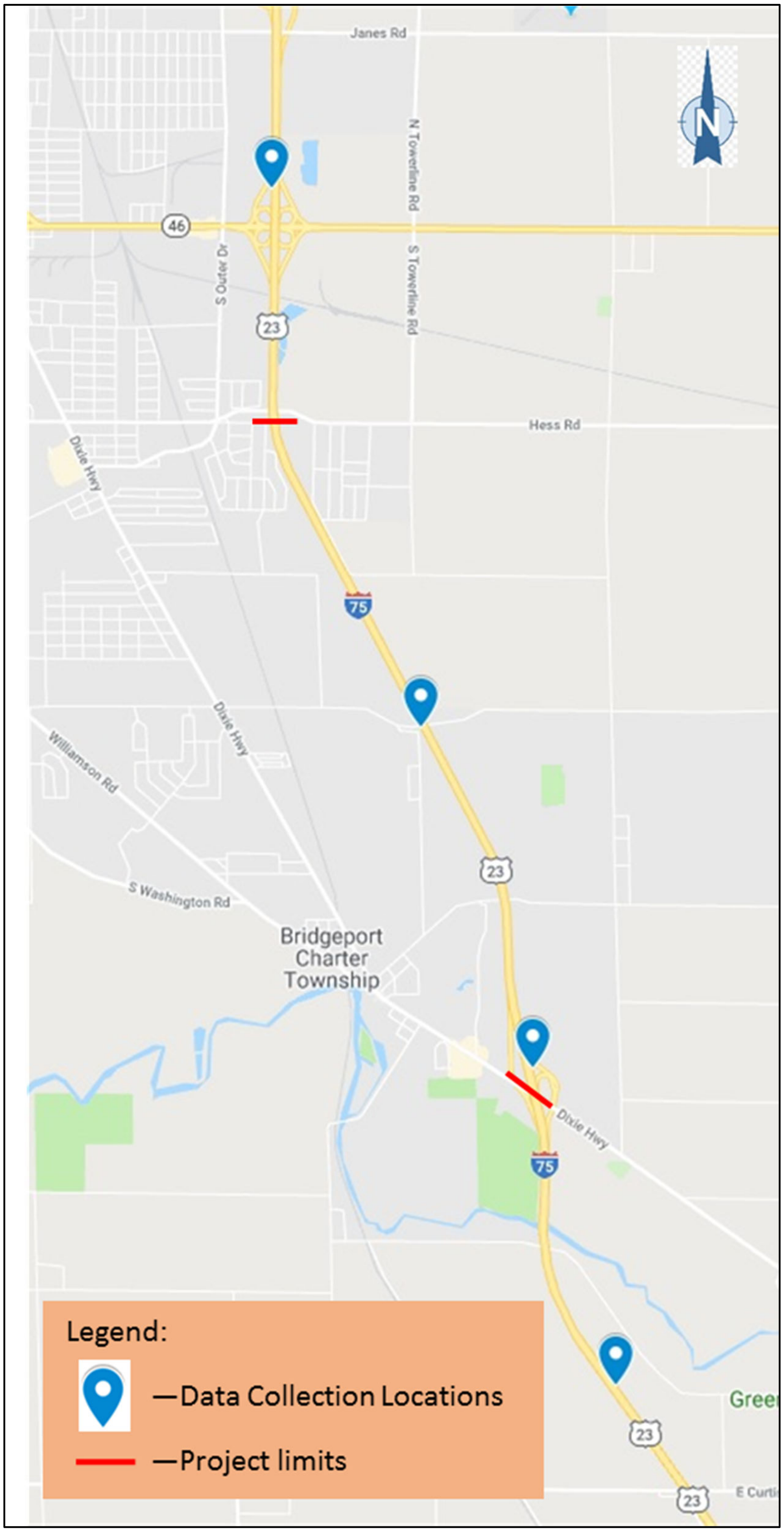


Figure 38. Data collection locations.

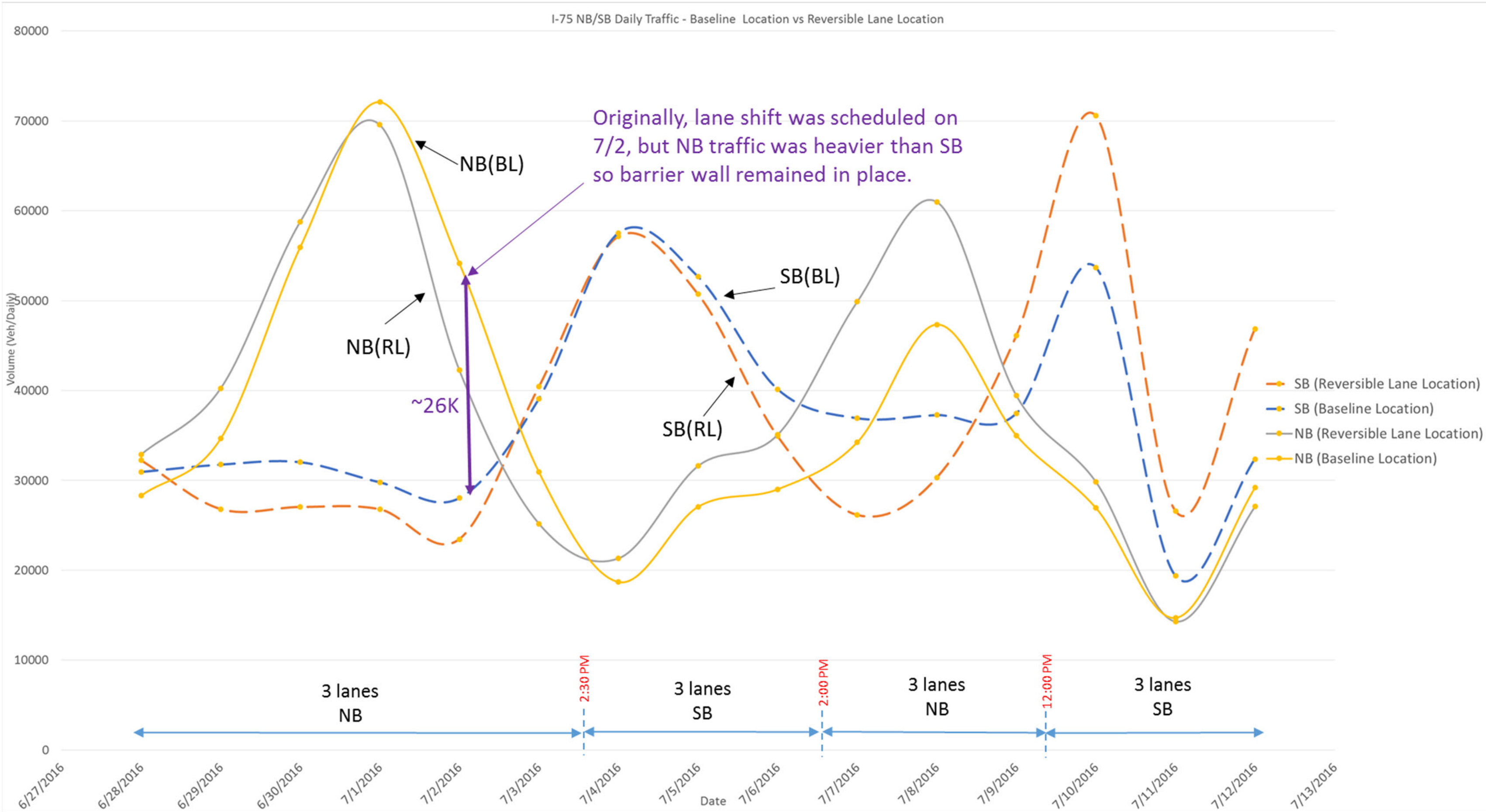


Figure 39. I-75 daily traffic volumes (*with* reversible-lane change times).

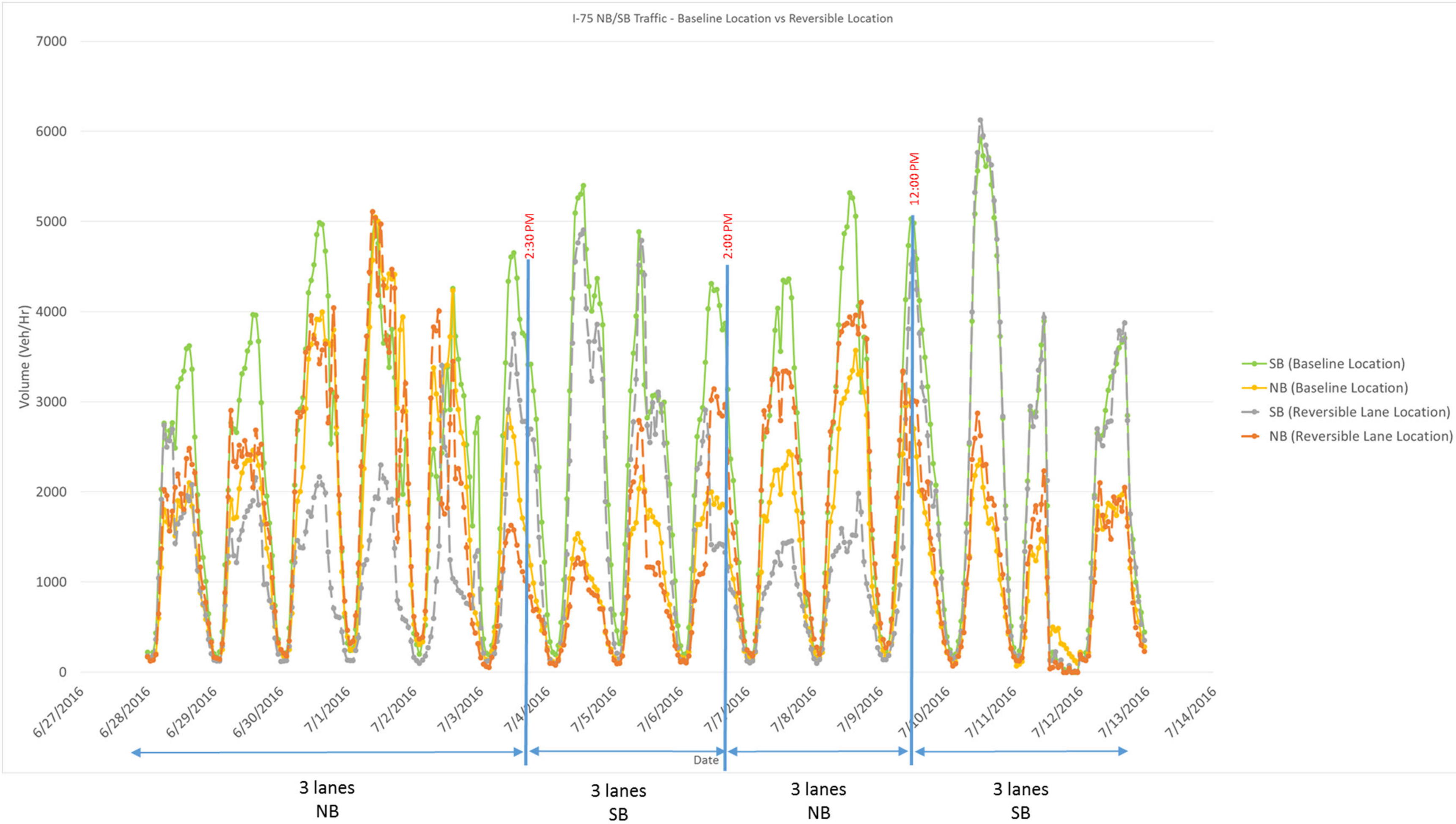


Figure 40. I-75 hourly traffic volumes (*with* reversible-lane change times).

Figures 41 and 42 illustrate the vehicle speeds and traffic volumes on the mainline for northbound direction and southbound direction, respectively. The graphs indicated that I-75 did not have daily peaks; rather, a peak period that spans the entire day from about 10:00 a.m. to 7:00 p.m., regardless of direction. In general, work zones will reduce capacity by at least 5% to 15% when the roadway is at or close to capacity due to narrow lanes or shoulders, barrier close to travel lane and other geometric changes. However, by implementing the reversible lane, it appears that capacity is maintained and vehicle speeds were within ±5% of baselines speeds.

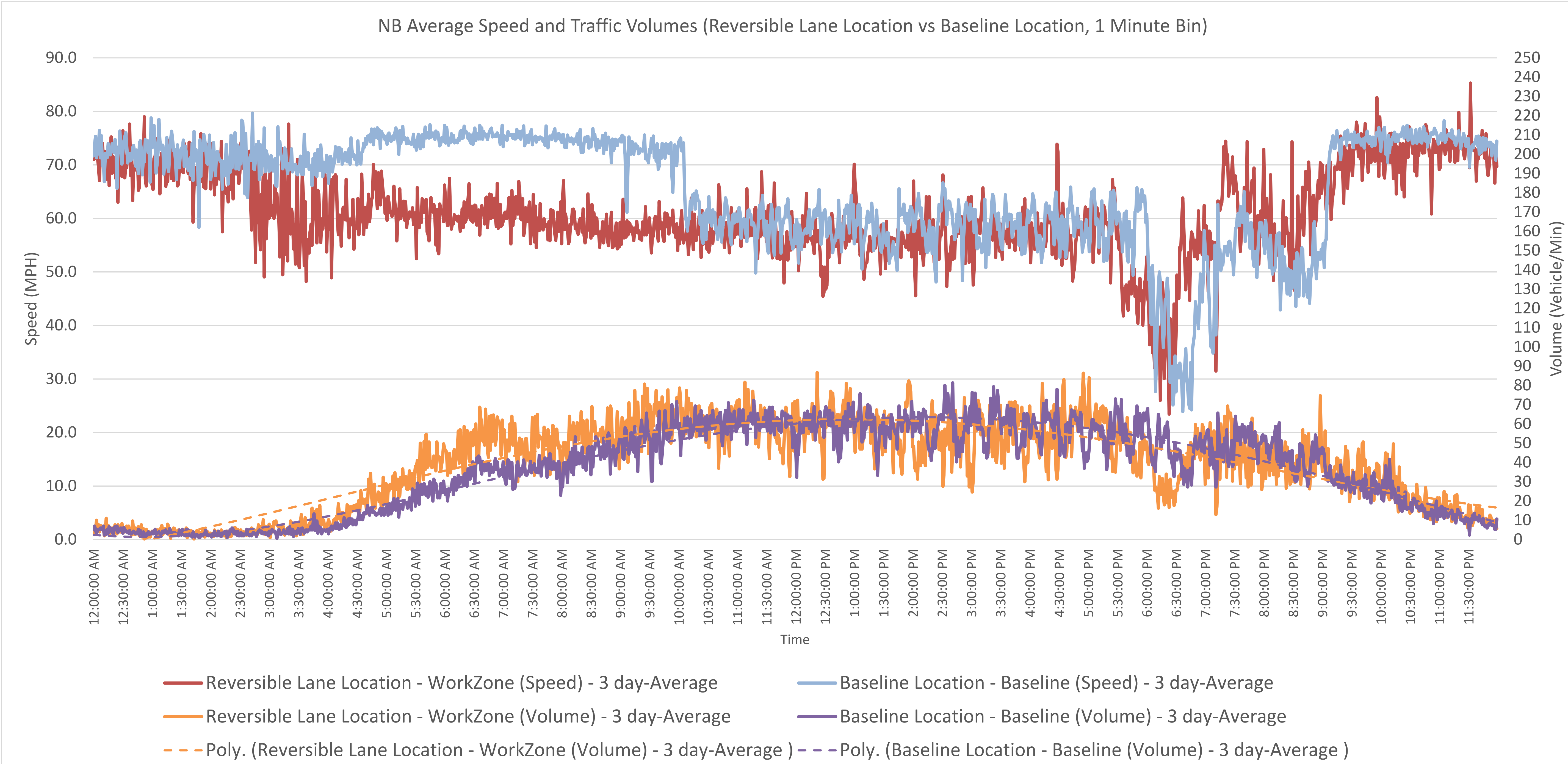


Figure 41. Northbound average speed and traffic volumes (10:00 a.m. to 7:00 p.m.).

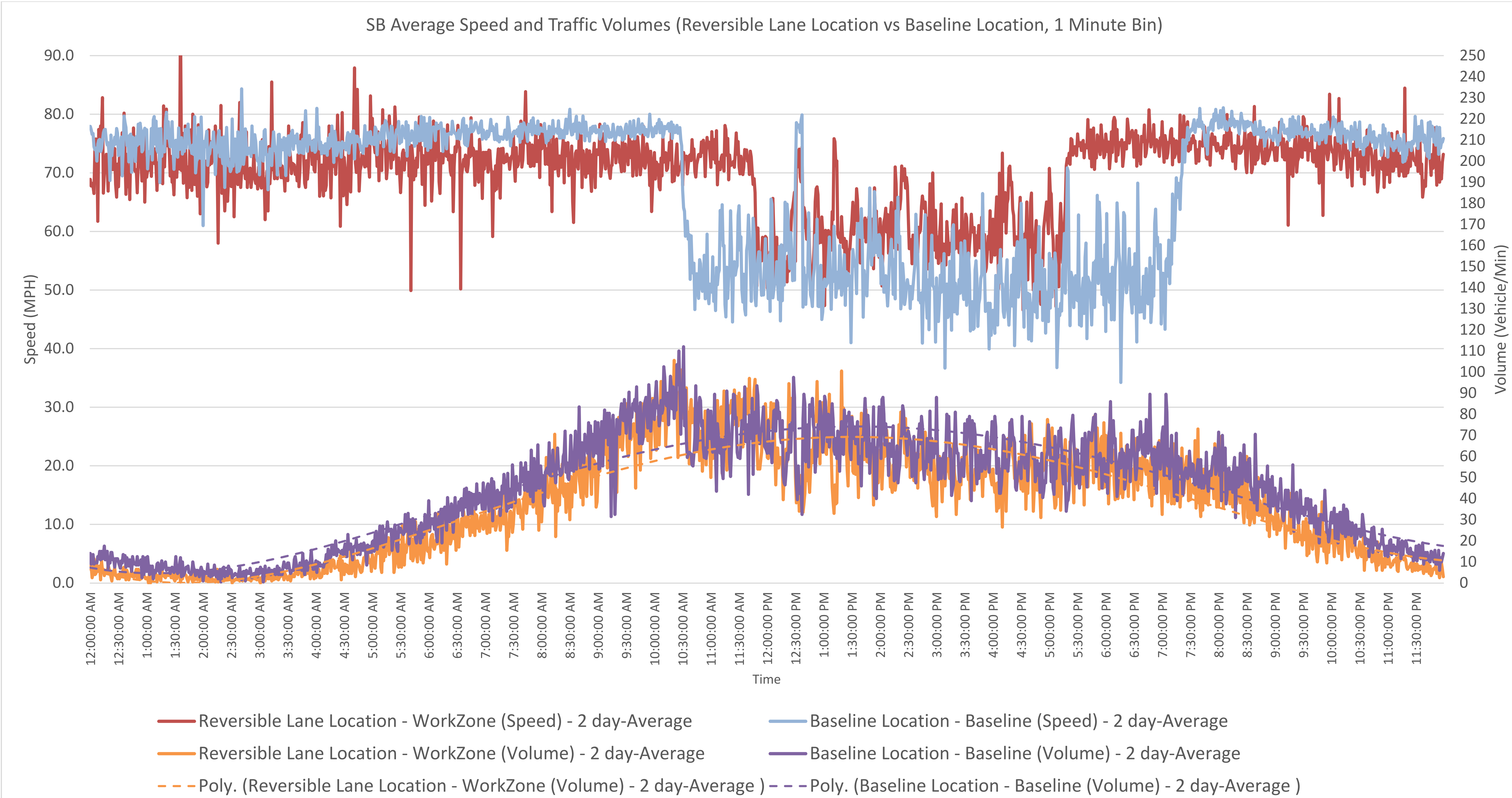


Figure 42. Southbound average speed and traffic volumes (10:00 a.m. to 7:00 p.m.).

7.3.1.2 Statistical Analysis of Vehicle Speed

The team calculated changes in the mean speeds and 85th percentile speeds for vehicles between *with* and *without* implementation of the reversible lane. Tables 43 and 44 show the comparison of mean speed and 85th percentile speed of vehicles on the mainline of the freeway and the statistical test results *with* and *without* the implementation of the reversible lane.

Table 43. Speed comparison—northbound direction baseline location vs. reversible-lane location.

Speed Comparison for NB I-75		Volume	Sample Size	Mean Speed (mph)	85th Percentile Speed (mph)	SD	Mean Speed t_{static}
1000-1100	Baseline	10734	692	66.52	77.00	14.60	**5.96**
	Reversible Lane	11037	507	61.18	70.00	15.81	
1100-1200	Baseline	10950	694	63.85	77.00	16.80	**4.00**
	Reversible Lane	10714	518	59.99	70.00	16.43	
1200-1300	Baseline	10734	692	66.52	77.00	14.60	**7.61**
	Reversible Lane	11093	511	59.40	71.00	17.02	
1300-1400	Baseline	10950	694	63.85	77.00	16.80	**5.88**
	Reversible Lane	10352	499	57.91	70.00	17.50	
1400-1500	Baseline	10734	692	66.52	77.00	14.60	**7.85**
	Reversible Lane	9157	485	58.45	72.00	19.05	
1500-1600	Baseline	10734	692	66.52	77.00	14.60	**8.29**
	Reversible Lane	9813	496	58.30	71.00	18.28	
1600-1700	Baseline	10950	694	63.85	77.00	16.80	**3.60**
	Reversible Lane	10543	488	60.15	72.00	17.80	
1700-1800	Baseline	8258	662	42.74	77.00	28.52	**-6.54**
	Reversible Lane	9560	490	52.74	72.00	23.35	
1800-1900	Baseline	8974	656	57.48	78.00	25.51	**10.49**
	Reversible Lane	6533	458	39.79	72.00	29.15	

(Bold indicates significance at the 95% confidence level, α = .05)

The *t*-test results indicated that changes in northbound mean speed during implementation periods of the reversible lane were statistically significant for all time periods. However, the work zone within these congested daily periods was able to maintain traffic volumes and speeds throughout the day.

As Table 44 shows, the southbound mean speeds of vehicles on the mainline of the freeway increased for all time periods from 10:00 a.m. to 7:00 p.m.

Table 44. Speed comparison—southbound direction baseline location vs. reversible-lane location.

Speed Comparison for SB I-75		Volume	Sample Size	Mean Speed (mph)	85th Percentile Speed (mph)	SD	Mean Speed t_{static}
1000-1100	Baseline	9537	480	62.37	83.00	27.60	**-7.48**
	Reversible Lane	9347	359	71.97	77.00	4.63	
1100-1200	Baseline	8451	480	44.37	81.00	34.04	**-13.50**
	Reversible Lane	9172	359	67.72	76.00	14.42	
1200-1300	Baseline	8125	480	43.62	80.00	34.48	**-4.67**
	Reversible Lane	7591	332	53.05	73.00	23.07	
1300-1400	Baseline	8287	480	43.51	80.15	34.15	**-4.69**
	Reversible Lane	7453	346	53.25	74.00	25.60	
1400-1500	Baseline	7757	480	44.56	80.00	33.47	**-6.06**
	Reversible Lane	7030	360	56.84	76.00	25.28	
1500-1600	Baseline	7360	480	43.74	80.00	34.18	**-5.51**
	Reversible Lane	6305	360	55.35	77.00	26.87	
1600-1700	Baseline	7051	480	44.27	81.00	34.57	**-6.50**
	Reversible Lane	6337	351	57.83	78.00	25.57	
1700-1800	Baseline	7062	480	44.58	82.00	35.04	**-13.61**
	Reversible Lane	6643	359	69.29	78.00	16.28	
1800-1900	Baseline	7363	480	44.79	82.00	35.27	**-18.60**
	Reversible Lane	6398	359	75.04	79.00	4.44	

(Bold indicates significance at the 95% confidence level, α = .05)

The *t*-test results indicated the changes in mean speed during implementation periods of the reversible lane were statistically significant for time periods from 10:00 a.m. to 7:00 p.m.

After implementing the reversible lane, the vehicle speeds were maintained on the mainline in both directions of the freeway—despite volume increases.

7.3.1.3 Comparison of Results for Travel Time

Comparing travel times through the work zone is a good measurement of effectiveness to determine the effect of implementing the reversible lane. The reversible-lane operation maintains capacity through the work zone and is expected to have no effect on vehicle speeds, which will result in similar travel times to the baseline.

The team analyzed the travel times of vehicles on the mainline of the freeway through the project limit during the daily the peak hours (10:00 a.m. to 7:00 p.m.) to determine the effects of implementing the reversible lane over the 6.5-mi segment.

Figures 43 and 44 illustrate travel time through the project limits for northbound and southbound peak direction periods, respectively. The graphs indicated that the reversible lane was generally able to maintain travel times when compared to the baseline conditions. Travel times were maintained during the later afternoon period when traffic volumes increased by 20% to 30%.

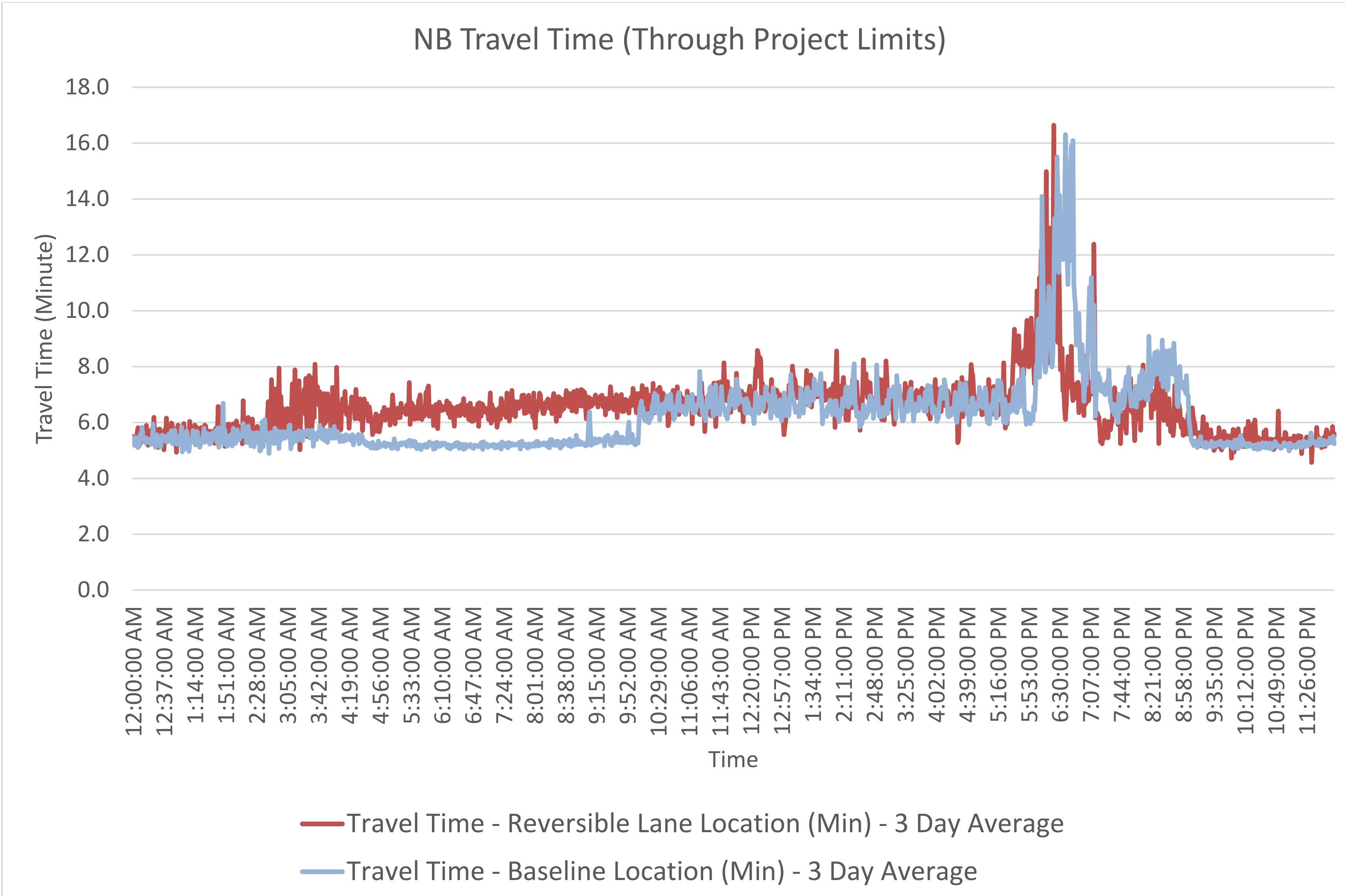


Figure 43. Northbound travel time (distance: 6.5 mi).

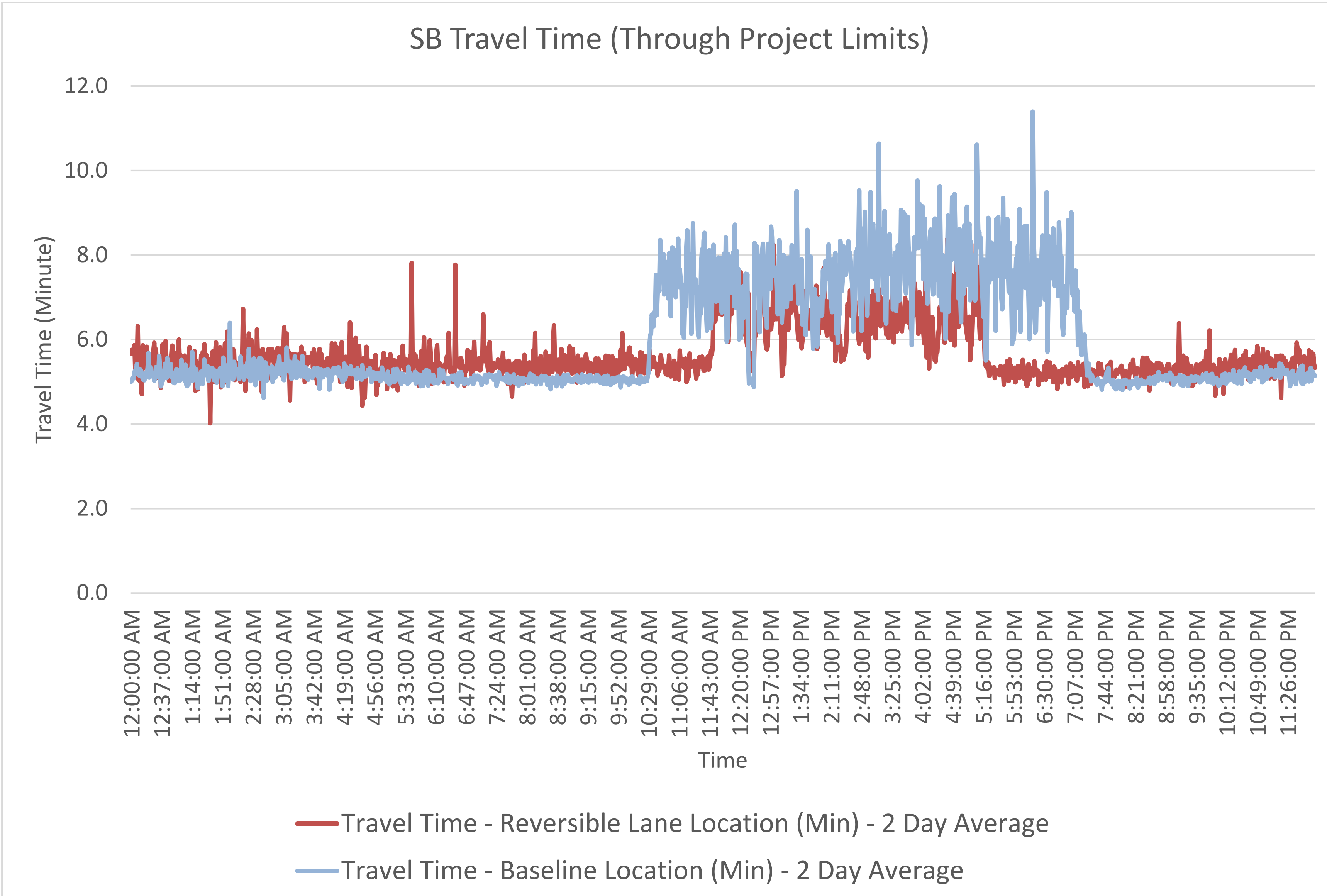


Figure 44. Southbound travel time (distance: 6.5 mi).

7.3.1.4 Statistical Analysis of Travel Time

Tables 45 and 46 show the comparison of average travel time *with* and *without* the reversible lane.

As Table 45 shows, the NB average travel time through the project limits was maintained or lower *with* the reversible-lane operation—except during the late afternoon when traffic volumes increased by 20% to 30%. The *t*-test results indicated the changes in travel time were statistically significant for most time periods.

Table 45. Travel time comparison—northbound direction baseline location vs. reversible-lane location.

Travel Time Comparison for NB I-75		Volume	Sample Size	Average Travel Time (Min)	85th Percentile Travel Time (Min)	SD	Mean Travel Time t_{static}
1000-1100	Baseline	10734	180	6.35	8.49	1.79	**-2.02**
	Reversible Lane	11037	179	6.68	8.47	1.26	
1100-1200	Baseline	10950	180	6.82	9.25	2.53	-1.16
	Reversible Lane	10714	180	7.15	8.80	2.87	
1200-1300	Baseline	10581	180	7.87	10.40	6.11	1.22
	Reversible Lane	11093	180	7.24	8.80	3.43	
1300-1400	Baseline	10621	180	8.16	11.70	5.79	0.83
	Reversible Lane	10352	180	7.69	9.47	5.05	
1400-1500	Baseline	10636	180	9.57	10.20	11.00	1.57
	Reversible Lane	9157	179	8.06	10.27	6.76	
1500-1600	Baseline	10817	180	8.83	11.74	7.97	1.30
	Reversible Lane	9813	179	7.91	9.46	5.08	
1600-1700	Baseline	10337	180	8.58	9.90	7.52	**1.83**
	Reversible Lane	10543	175	7.40	8.95	4.25	
1700-1800	Baseline	10101	180	8.05	10.18	6.71	**-3.43**
	Reversible Lane	9560	180	11.93	17.35	13.57	
1800-1900	Baseline	8258	180	18.61	39.44	16.84	**-3.57**
	Reversible Lane	6533	180	28.46	61.16	32.97	

(Bold indicates significance at the 95% confidence level, $\alpha = .05$)

As Table 46 shows, the SB average travel time through the project limits decreased for all time periods from 10:00 a.m. to 7:00 p.m. The *t*-test results indicated the changes in travel time were statistically significant for all southbound time periods.

Table 46. Travel time comparison—southbound direction baseline location vs. reversible-lane location.

Travel Time Comparison for SB I-75		Volume	Sample Size	Average Travel Time (Min)	85th Percentile Travel Time (Min)	SD	Mean Travel Time t_{static}
1000-1100	Baseline	9537	120	6.25	28.62	16.77	0.54
	Reversible Lane	9347	120	5.42	5.66	0.26	
1100-1200	Baseline	8451	120	8.79	54.29	28.11	1.17
	Reversible Lane	9172	120	5.76	5.83	4.58	
1200-1300	Baseline	8125	120	8.94	47.27	21.76	0.66
	Reversible Lane	7591	120	7.35	17.76	14.99	
1300-1400	Baseline	8287	120	8.96	50.10	21.93	0.62
	Reversible Lane	7453	120	7.32	14.09	18.93	
1400-1500	Baseline	7757	120	8.75	48.44	22.44	0.91
	Reversible Lane	7030	120	6.86	11.70	3.14	
1500-1600	Baseline	7360	120	8.91	49.09	21.82	0.92
	Reversible Lane	6305	120	7.05	12.22	3.79	
1600-1700	Baseline	7051	120	8.81	55.84	24.44	0.92
	Reversible Lane	6337	120	6.74	12.35	3.76	
1700-1800	Baseline	7062	120	8.75	53.73	29.40	1.16
	Reversible Lane	6643	120	5.63	5.96	2.39	
1800-1900	Baseline	7363	120	8.71	50.62	23.24	**1.65**
	Reversible Lane	6398	120	5.20	5.40	0.21	

(Bold indicates significance at the 95% confidence level, α = .05)

After implementing the reversible lane, the travel time through the project limits were generally maintained or lower in both directions.

7.3.1.5 Comparison of Results for Frequency of Headway

Headway is a good measure of congestion and lack of passing opportunities created by the traffic mix; it is also a good measure of safety as lane changing and frequent passing generally lead to conflicts and the likelihood of crashes. In general, a longer headway accepted by a merging vehicle is safer than a shorter headway.

The team examined the headways accepted by following vehicles to see if there were any differences between the *with* and *without* implementation of the reversible lane. The team conducted an analysis of vehicles headways on the mainline of the freeway at the baseline location and the reversible-lane location to determine the average values and distribution for both northbound and southbound peak direction periods.

As mentioned above, the team used the K-S test to judge how faithfully a distribution fits the sample data. The team adopted the K-S test to determine the goodness-of-fit in the work zone traffic condition.

Table 47 summarizes the K-S test results of the northbound peak direction period *vs. reversible-lane location.*

Table 47. K-S test results for the northbound peak direction period.

	Northbound Peak Direction Period	
	Baseline Location	**Reversible-Lane Location**
Sample Size	3,940	3,782
Mean Headway (seconds)	3.31	3.14
Median Headway (seconds)	3.00	2.86
Maximum difference (*D*)		0.08
Significance		Yes

Figure 45 presents a visual performance comparison of headway distributions through a cumulative distribution function in the peak hours (10:00 a.m. to 7:00 a.m.) at the baseline location and the reversible-lane location. The team observed a shift in the headway distribution toward the shorter headway at the reversible-lane location compared to baseline location. The mean value of headway was 3.31 seconds at baseline location as opposed to 3.14 seconds at reversible-lane location. With the significance level α of 0.05 and the sample size more than 40, the critical statistic of the K-S test for the maximum difference between the cumulative distributions, D, was 0.03. The results of the K-S test (baseline location vs. reversible-lane location) show a value of D of 0.08 (greater than the critical value of 0.03), which suggests the differences in the two cumulative distributions are statistically significant.

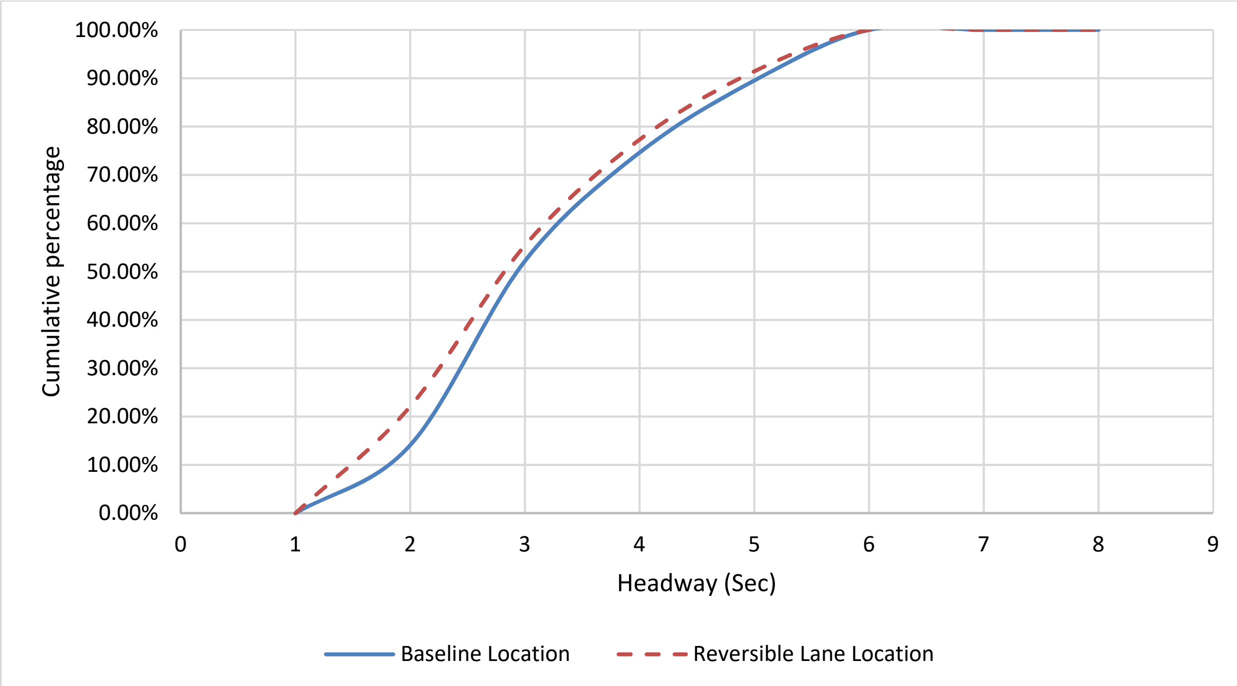


Figure 45. Cumulative headway distribution plot—northbound peak direction period—baseline location vs. reversible-lane location (10:00 a.m. to 7:00 p.m.).

Table 48 summarizes the K-S test results of the southbound peak direction *vs. reversible-lane location.*

Table 48. K-S test results for the southbound peak direction period.

	Southbound Peak Direction Period	
	Baseline Location	**Reversible-Lane Location**
Sample Size	3,392	2,945
Mean Headway (seconds)	3.56	3.10
Median Headway (seconds)	3.53	2.86
Maximum difference (*D*)		0.16
Significance		Yes

Figure 46 presents a visual performance comparison of headway distributions through a cumulative distribution function in the peak hours (10:00 a.m. to 7:00 p.m.) at the baseline location and the reversible-lane location. The team observed a shift in the headway distribution toward shorter headway at the reversible-lane location compared to the baseline location. The mean value of headway was 3.56 seconds at baseline location as opposed to 3.10 seconds at the reversible-lane location. With the significance level α of 0.05 and the sample size more than 40, the critical statistic of the K-S test for the maximum difference between the cumulative distributions, *D*, was 0.03. The results of the K-S test for (baseline location vs. reversible-lane location) shows a value of D of 0.16 (greater than the critical value of 0.03), which suggests the differences in the two cumulative distributions are statistically significant.

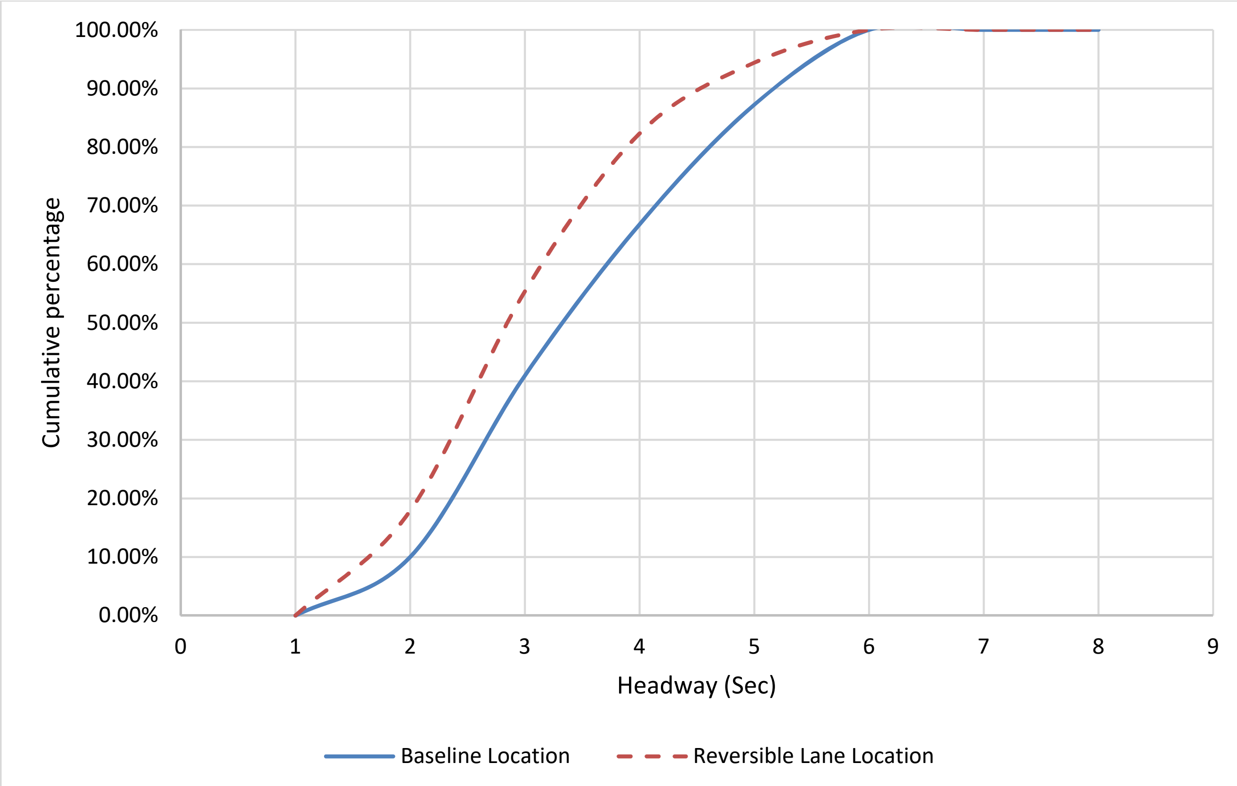


Figure 46. Cumulative headway distribution plot—southbound peak direction period—baseline location vs. reversible-lane location (10:00 a.m. to 7:00 p.m.).

The headways of vehicles on the mainline of the freeway at reversible-lane location exhibited a decrease in both northbound peak direction and southbound peak direction periods. The result of the K-S test indicated that the differences in the two cumulative distributions were statistically significant. The late afternoon traffic volume increase may have contributed to shorter headways. It can be reasonably concluded that although the mean headway decreased, it remained above 3 seconds.

7.3.2 Location: I-94, Maplewood, Minnesota

7.3.2.1 Comparison of Results for Vehicle Speeds

The team collected data at four locations on I-94—two within the work zone (in the reversible-lane configuration) and one each upstream and downstream (outside the work zone). Figure 47 illustrates the data collection locations.

Figure 48 illustrates the baseline traffic ADT volumes as well as the volumes carried by the work zone in the reversible-lane configuration for both northbound and southbound directions. I-94 carries commuting traffic and this evaluation showcases the capability of a reversible lane to manage demand. Based on daily peak period demand, as Figure 48 shows, the reversible operation was changed over during the mid-afternoon or early evening.

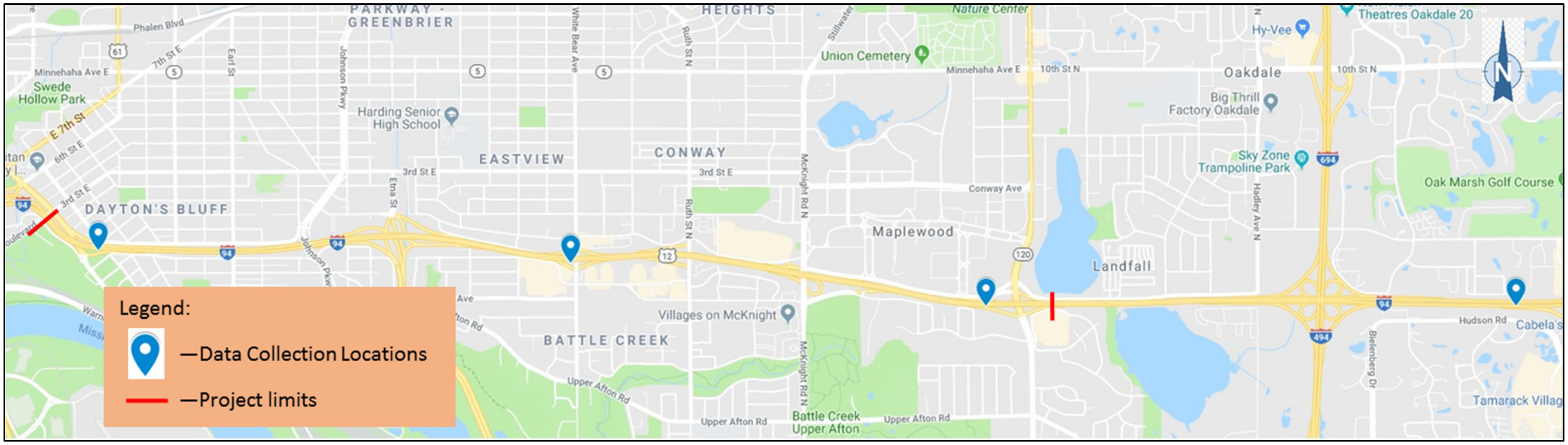


Figure 47. Data collection locations.

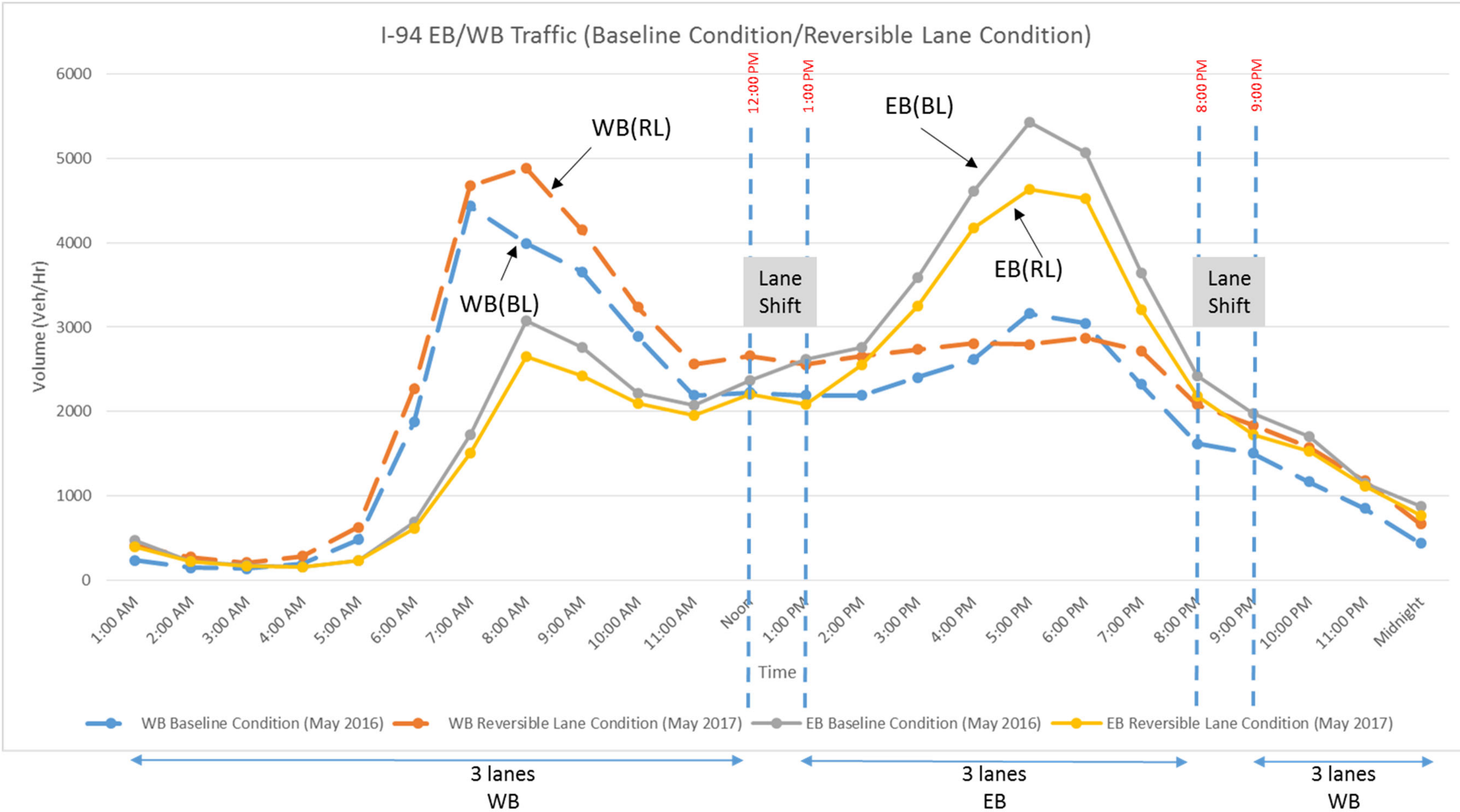


Figure 48. I-94 hourly traffic volumes.

Figures 49 and 50 illustrate the vehicle speeds and traffic volumes on the mainline for the a.m. peak westbound direction and the p.m. peak eastbound direction, respectively. In general, for the a.m. peak westbound direction, it appears that the reversible lane resulted in improved mainline performance. However, for the p.m. peak eastbound direction, implementing the reversible lane reduced the mainline speeds. In general, work zones will reduce capacity by at least 5% to 15% when the roadway is at or close to capacity due to narrow lanes or shoulders, barrier close to travel lane and other geometric changes. However, by implementing the reversible lane, it appears that capacity was generally maintained and vehicle speeds were within ±5% of baselines speeds.

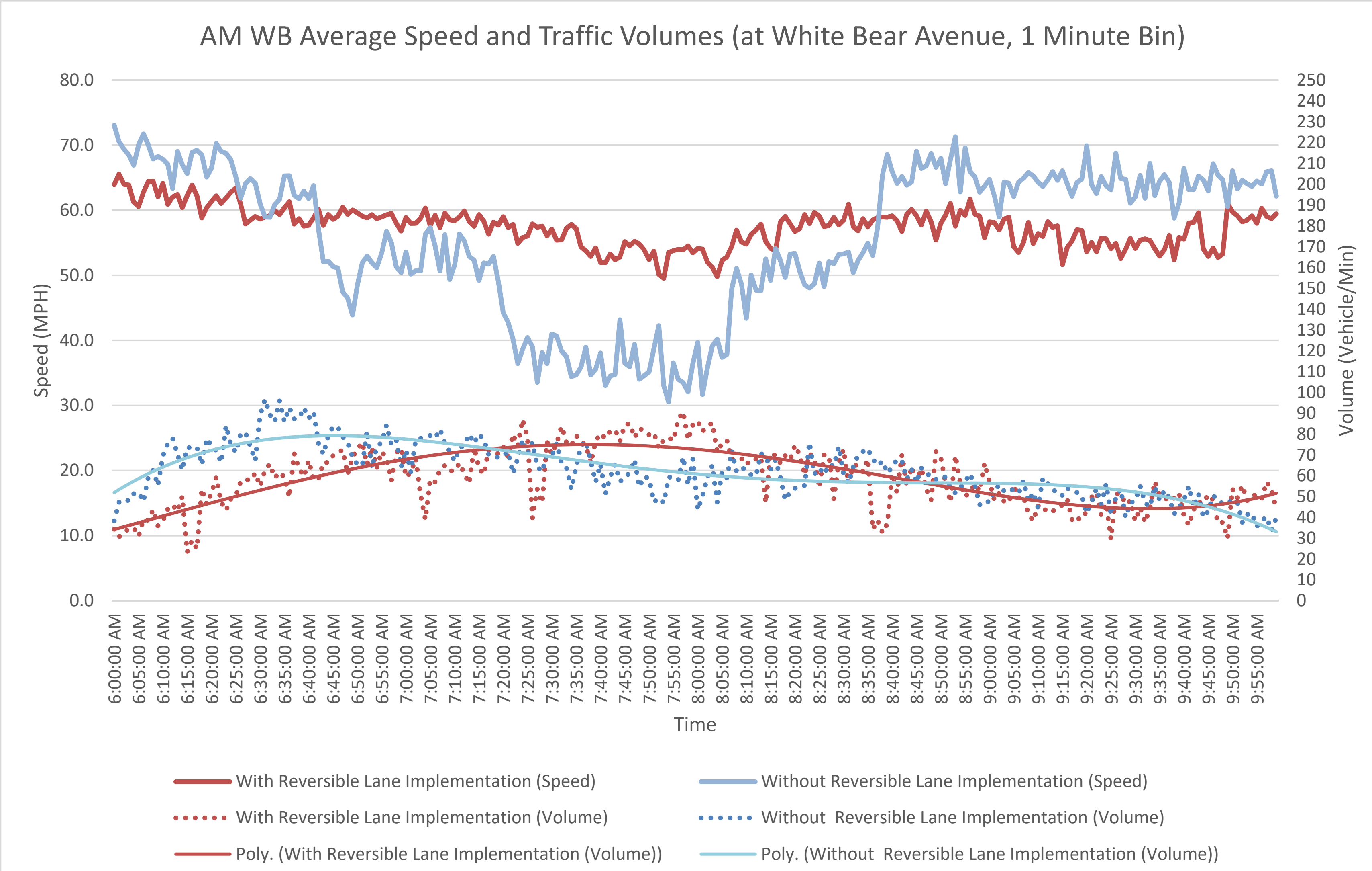


Figure 49. A.M. eastbound average speed and traffic volumes.

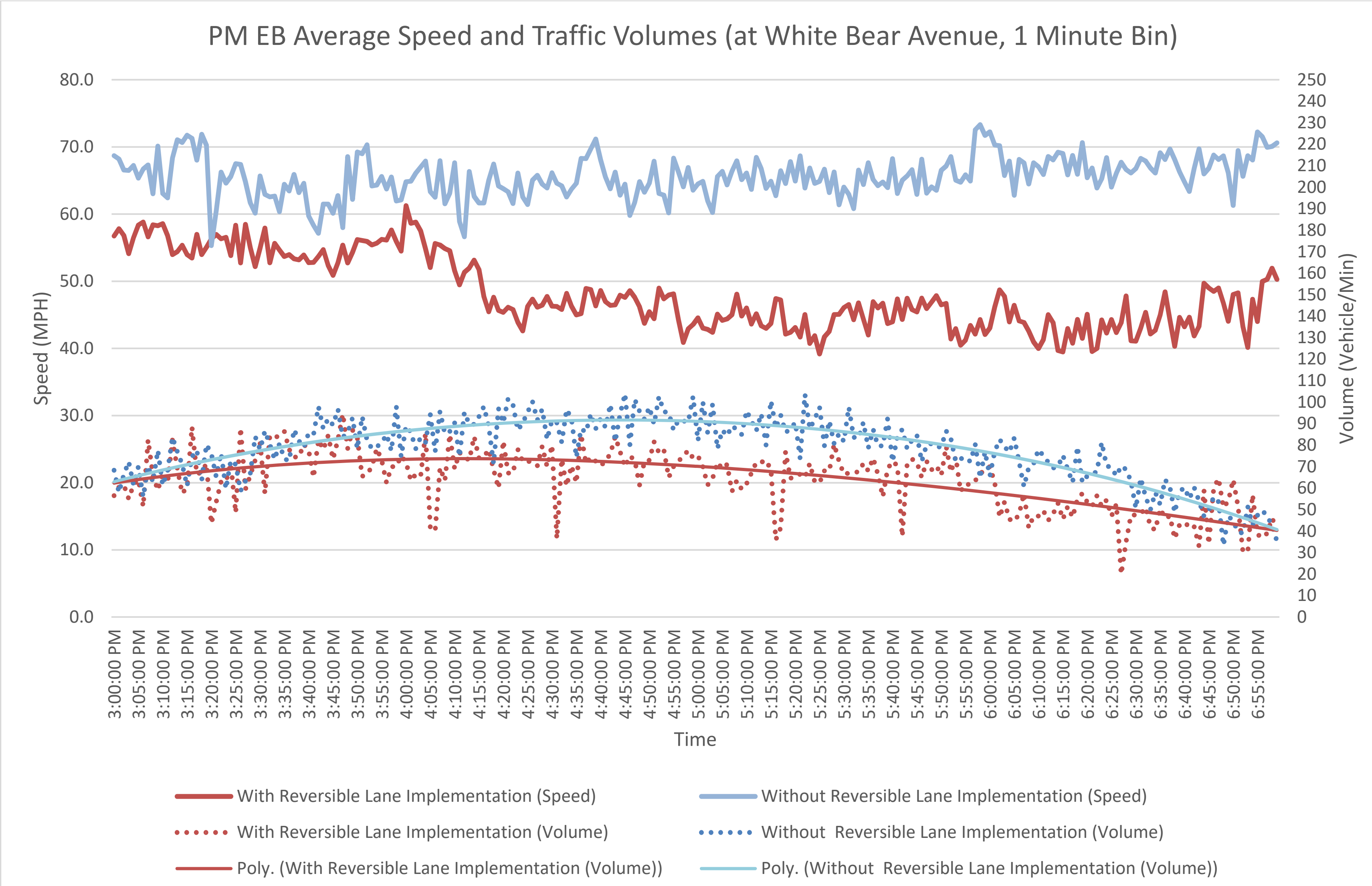


Figure 50. P.M. eastbound average speed and traffic volumes.

7.3.2.2 Statistical Analysis of Vehicle Speed

The team calculated changes in the mean speeds and 85th percentile speeds for vehicles between *with* and *without* implementation of the reversible lane. Tables 49 and 50 show the comparison of mean speed and 85th percentile speed of vehicles on the mainline of the freeway and the statistical test results *with* and *without* implementation of the reversible lane.

As Table 49 shows, the a.m. peak westbound mean speeds of vehicles on the mainline of the freeway generally improved in spite of additional traffic volumes. The *t*-test results indicated statistically significant changes in mean speed during the periods of implementation of the reversible lane between 7:00 a.m. to 10:00 a.m.

Table 49. Speed comparison—(a.m. peak westbound) *without* reversible lane vs. *with* reversible lane.

Speed Comparison for WB I-94		Volume	Sample Size	Mean Speed (mph)	85th Percentile Speed (mph)	SD	Mean Speed t_{static}
0600-0700	Baseline	13200	540	60.46	72.47	15.08	-0.62
	With Reversible Lane	9748	531	60.87	64.00	3.37	
0700-0800	Baseline	12073	539	39.36	68.00	24.08	**-15.68**
	With Reversible Lane	12870	525	56.21	60.00	6.47	
0800-0900	Baseline	10954	540	53.67	71.79	21.29	**-3.95**
	With Reversible Lane	11348	525	57.43	62.00	5.84	
0900-1000	Baseline	8679	540	63.41	72.23	8.61	**12.09**
	With Reversible Lane	8342	528	54.83	62.00	13.91	

(Bold indicates significance at the 95% confidence level, $\alpha = .05$)

As Table 50 shows, the p.m. peak eastbound mean speeds of vehicles on the mainline of the freeway decreased for all time periods from 3:00 p.m. to 7:00 p.m. The *t*-test results indicated statistically significant increases in all mean speed during the periods *with* the reversible lane.

Table 50. Speed comparison—(p.m. peak eastbound) *without* reversible lane vs. *with* reversible lane.

Speed Comparison for EB I-94		Volume	Sample Size	Mean Speed (mph)	85th Percentile Speed (mph)	SD	Mean Speed t_{static}
1500-1600	Without Reversible Lane	13783	540	64.66	70.29	9.28	**17.43**
	With Reversible Lane	8486	357	54.81	64.00	7.55	
1600-1700	Without Reversible Lane	16305	540	64.35	69.45	9.57	**18.31**
	With Reversible Lane	8556	349	45.30	63.00	17.86	
1700-1800	Without Reversible Lane	15253	540	65.45	69.65	6.18	**22.89**
	With Reversible Lane	7995	351	40.70	63.00	19.63	
1800-1900	Without Reversible Lane	10979	540	67.39	72.60	6.73	**19.54**
	With Reversible Lane	5710	329	43.44	66.00	21.60	

(Bold indicates significance at the 95% confidence level, X = .05)

After implementing the reversible lane, the speeds of vehicles on the mainline of the freeway generally increased in the a.m. peak westbound direction. The speeds of vehicles on the mainline of the freeway decreased in the p.m. peak eastbound direction. However, the reversible-lane operation was able to maintain average vehicle speeds at or close to the work zone posted speed limit (45 mph). Therefore, it seems that implementing the reversible lane was able to achieve the mobility goal of the work zone.

7.3.2.3 Comparison of Results for Travel Time

The comparison of travel times through the work zone is a good MOE to determine the effect of reversible lanes. The team conducted an analysis of travel time of vehicles on the mainline of the freeway through the project limits of the project area in the peak hours (6:00 a.m. to 10:00 a.m. for WB and 3:00 p.m. to 7:00 p.m. for EB) to determine the effects of implementing the reversible lane.

Figure 51 illustrates that travel times through the project limits for westbound direction significantly improved during the period of highest congestion. Figure 52 illustrates that although speeds were lower at the mid-point of the reversible lane, travel time through the project limits (4.6 mi) for the eastbound direction improved.

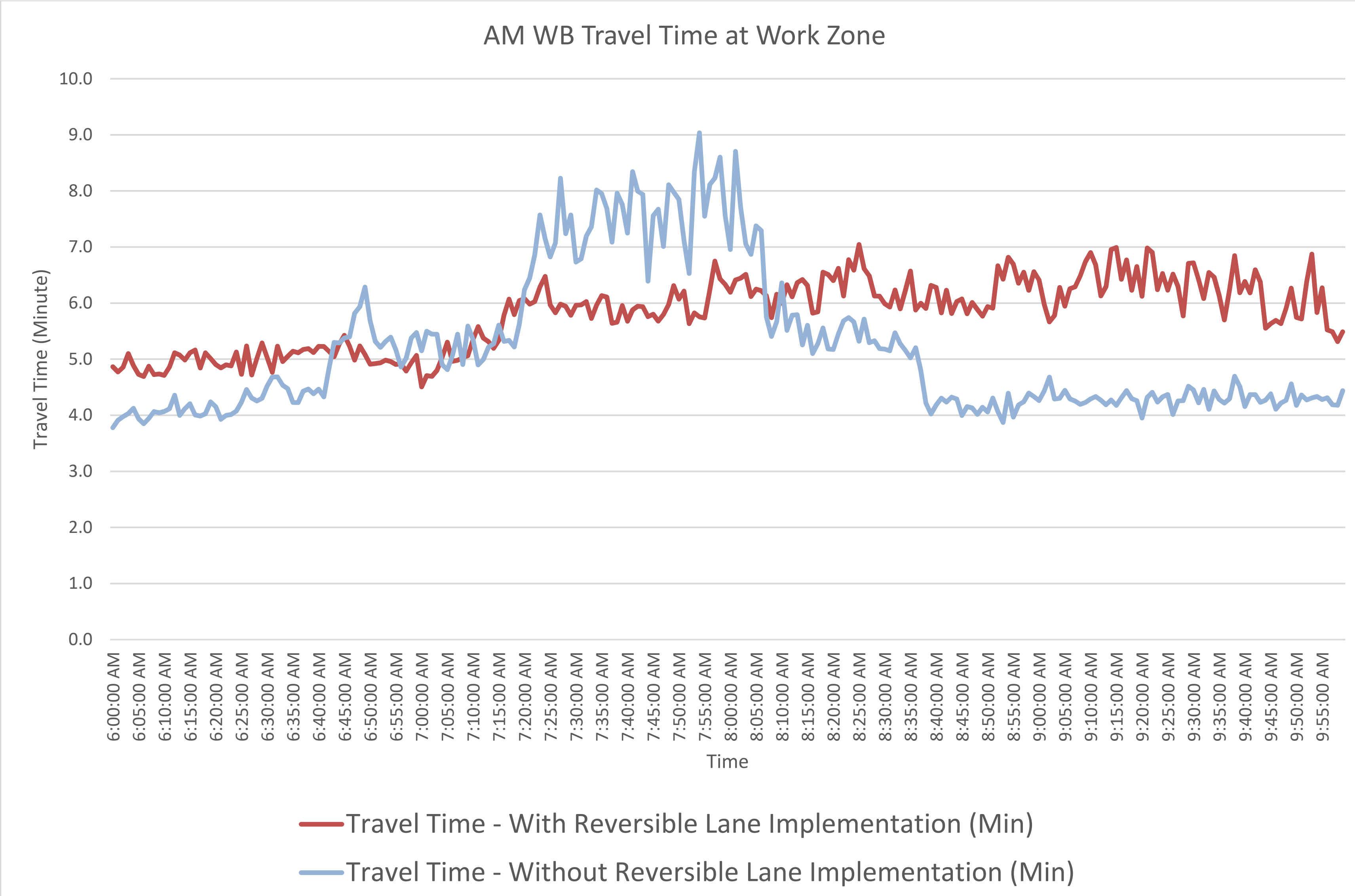


Figure 51. A.M. peak westbound travel time (distance: 4.6 mi).

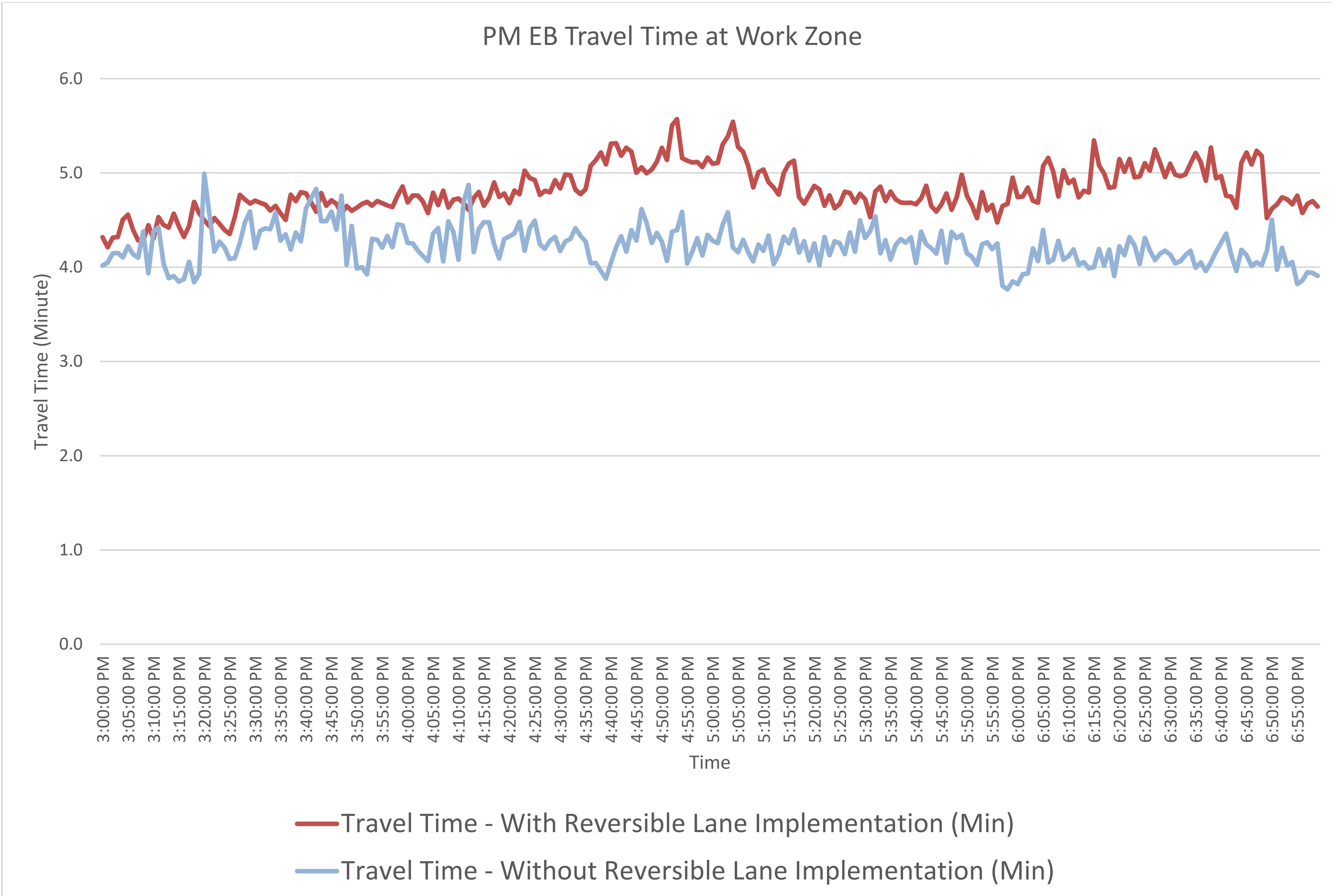


Figure 52. P.M. peak eastbound travel time (distance: 4.6 mi).

7.3.2.4 Statistical Analysis of Travel Time

The team used a comparison of travel times to evaluate the effect of the reversible lane and determine if the reversible lane caused changes in travel characteristics. The team used the *t*-statistic to evaluate the effect of implementing the reversible-lane condition. The team calculated changes in average travel time and the 85th percentile travel time for vehicles traveling through the project limits between the *with* and *without* the reversible lane. Tables 51 and 52 show the comparison of average travel time and the 85th percentile speed of travel along with the statistical test results *with* and *without* the reversible lane.

Table 51 shows that WB average travel time through the project limits generally decreased. The *t*-test results indicated the changes of travel time during the periods of implementing the reversible lane were statistically significant.

Table 51. Travel time comparison—(a.m. peak westbound) *without* reversible lane vs. *with* reversible lane.

Travel Time Comparison for WB I-94		Volume	Sample Size	Average Travel Time (Min)	85th Percentile Travel Time (Min)	SD	Mean Travel Time t_{static}
0600-0700	Without Reversible Lane	13200	180	5.23	4.84	3.86	**2.31**
	With Reversible Lane	9748	177	4.57	4.77	0.21	
0700-0800	Without Reversible Lane	12073	180	12.63	19.74	17.26	**5.96**
	With Reversible Lane	12870	175	4.96	5.26	0.38	
0800-0900	Without Reversible Lane	10954	180	7.60	12.28	8.44	**4.39**
	With Reversible Lane	11348	175	4.84	5.03	0.39	
0900-1000	Without Reversible Lane	8679	180	4.31	4.62	0.26	**-12.20**
	With Reversible Lane	8342	176	5.02	5.84	0.73	

(Bold indicates significance at the 95% confidence level, X = .05)

As Table 52 shows, the EB average travel time through the project limits increased for time periods from 3:00 p.m. to 7:00 p.m. The *t*-test results indicated the changes in travel time during the periods of implementing the reversible lane were statistically significant.

Table 52. Travel time comparison—(p.m. peak eastbound) *without* reversible lane vs. *with* reversible lane.

Travel Time Comparison for EB I-94		Volume	Sample Size	Average Travel Time (Min)	85th Percentile Travel Time (Min)	SD	Mean Travel Time t_{static}
1500-1600	Without Reversible Lane	13783	180	4.28	4.63	0.39	**-12.09**
	With Reversible Lane	8486	120	4.96	5.23	0.52	
1600-1700	Without Reversible Lane	16305	180	4.30	4.55	0.32	**-13.39**
	With Reversible Lane	8556	120	5.61	6.14	1.05	
1700-1800	Without Reversible Lane	15253	180	4.23	4.45	0.23	**-18.62**
	With Reversible Lane	7995	120	6.12	6.76	1.10	
1800-1900	Without Reversible Lane	10979	180	4.10	4.32	0.23	**-15.15**
	With Reversible Lane	5710	120	6.17	7.16	1.49	

(Bold indicates significance at the 95% confidence level, α = .05)

After implementing the reversible lane, the travel time through project limits improved in the morning peak period but showed a slight increase in the afternoon peak period. This increase was most likely attributable to the decreased capacity of the overall work zone due to other temporary lane changes. Although the changes varied, implementing the reversible-lane operation appeared to meet the work zone goal (i.e., maintaining vehicle speeds at or close to the posted speed limit 45 mph).

7.3.2.5 Comparison of Results for Frequency of Headway

The team examined the headways accepted by following vehicles to see if there were any differences between the *with* and *without* implementation of the reversible lane. The team conducted an analysis of headways of vehicles on the mainline of the freeway at one reversible-lane location to determine the average values and distribution for the a.m. peak westbound and p.m. peak eastbound peak directions.

As mentioned above, the team used the K-S test to judge how faithfully a distribution fits the sample data. The K-S test was adopted to determine the goodness-of-fit in the work zone traffic condition. Table 53 summarizes the K-S test results for the a.m. peak westbound direction.

Table 53. K-S test results for the a.m. peak westbound direction.

	A.M. Peak Westbound Direction	
	Baseline Location	Reversible-Lane Location
Sample Size	2,063	1,906
Mean Headway (seconds)	3.09	3.16
Median Headway (seconds)	2.86	3.00
Maximum difference (*D*)		0.06
Significance		Yes

Figure 53 presents a visual performance comparison of headway distributions through a cumulative distribution function in the a.m. peak westbound direction (6:00 a.m. to 10:00 a.m.) at the reversible-lane location. The team observed a slight shift in the headway distribution toward longer headways with the *without* reversible-lane condition compared to *with* the reversible-lane condition. The longer headways were observed for the *with* reversible-lane condition compared to the *without* reversible-lane condition starting from cumulative percentage at 35% and continuing to about a cumulative 95% of the distribution, with a maximum headway difference of 0.3 sec. The mean value of headway was 3.09 seconds at the *without* reversible-lane condition as opposed to 3.16 seconds at the *with* reversible-lane condition. With the significance level α of 0.05 and the sample size more than 40, the critical statistic of K-S test for the maximum difference between the cumulative distributions, *D*, is 0.04. The results of K-S test for (*without* reversible lane vs. *with* reversible lane) shows a value of D of 0.06 (greater than the critical value of 0.04), which suggests the differences in the two cumulative distributions are statistically significant.

Table 54 summarizes the K-S test results for the p.m. peak eastbound direction.

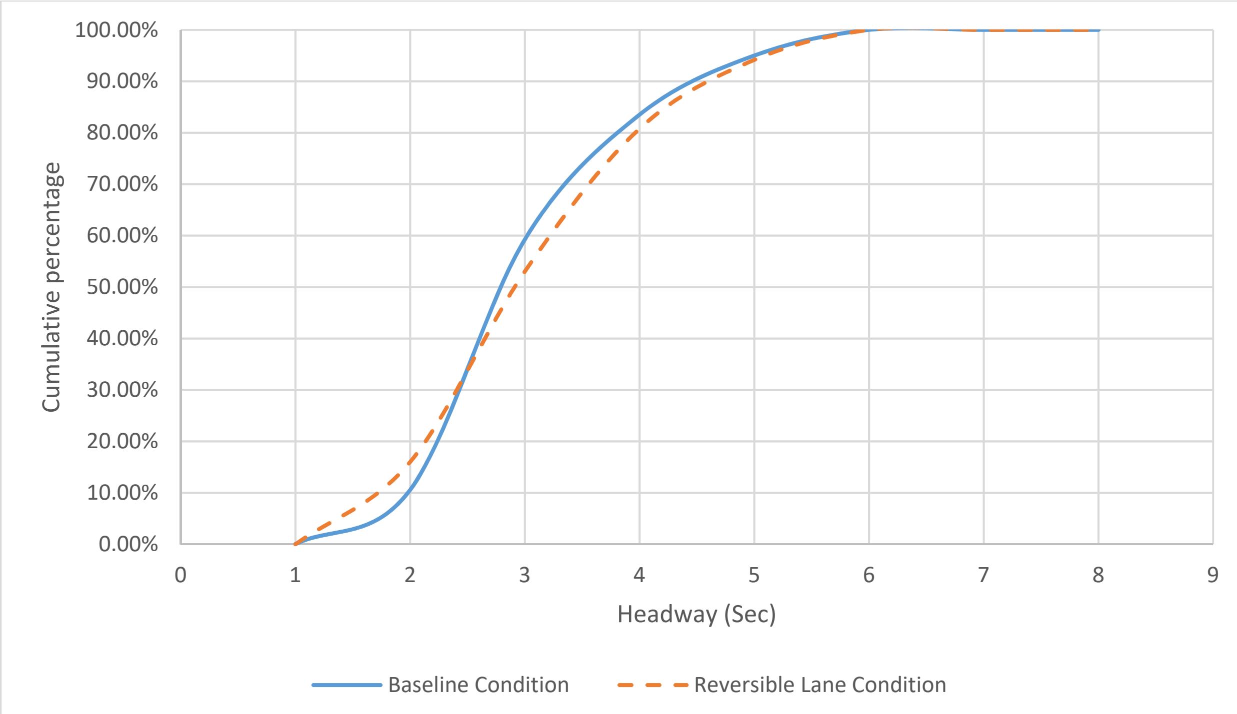


Figure 53. Cumulative headway distribution plot—(a.m. peak westbound) *without* reversible lane vs. *with* reversible lane (6:00 a.m. to 10:00 a.m.).

Table 54. K-S test results for the p.m. peak eastbound direction.

	P.M. Peak Eastbound Direction	
	Baseline Location	**Reversible-Lane Location**
Sample Size	2,145	1,338
Mean Headway (seconds)	2.52	2.89
Median Headway (seconds)	2.40	2.73
Maximum difference (*D*)		0.17
Significance		Yes

Figure 54 presents a visual performance comparison of headway distributions through a cumulative distribution function for the p.m. peak eastbound direction (3:00 p.m. to 7:00 p.m.) at the reversible-lane location. The team observed a slight shift in the headway distribution toward longer headways *with* the reversible-lane condition compared to *without* the reversible-lane condition. The mean headway value was 2.52 seconds for the *without* reversible-lane condition, as opposed to 2.89 seconds for the *with* reversible-lane condition. With the significance level α of 0.05 and the sample size more than 40, the critical statistic of K-S test for the maximum difference between the cumulative distributions, D, is 0.05. The results of K-S test for (*without* reversible lane vs. *with* reversible lane) shows a value of D of 0.17 (greater than the critical value of 0.05), which suggests the differences in the two cumulative distributions are statistically significant.

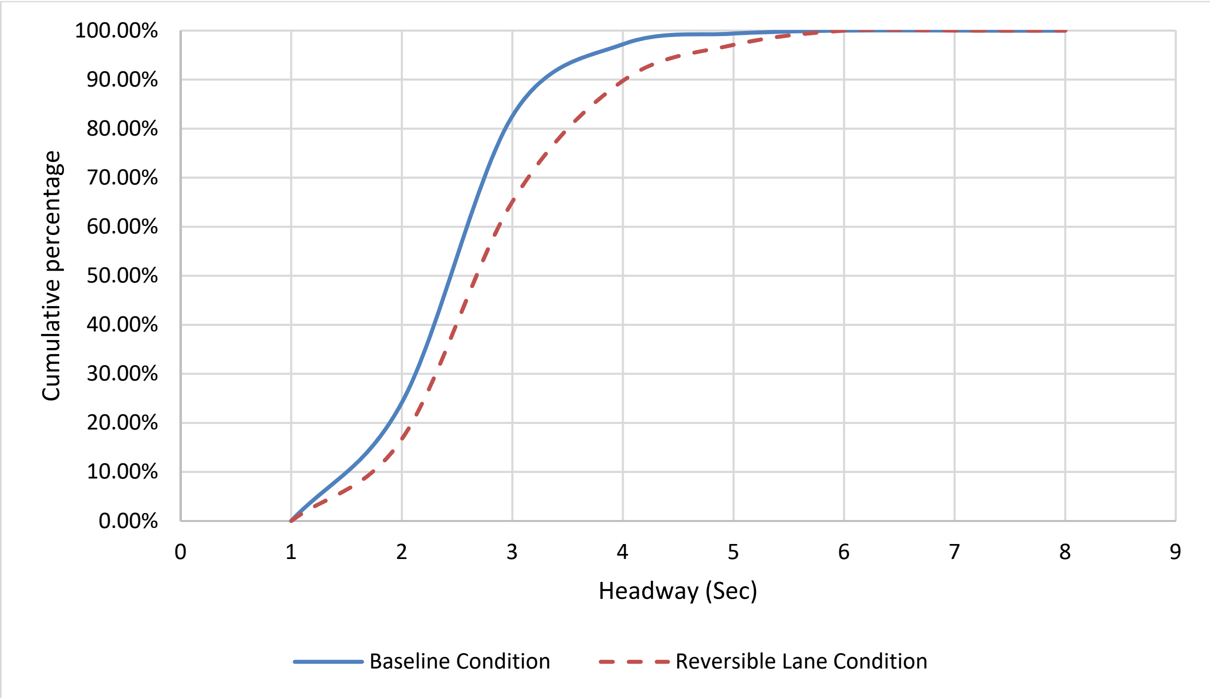


Figure 54. Cumulative headway distribution plot—(p.m. peak eastbound) *without* reversible lane vs. *with* reversible lane (3:00 p.m. to 7:00 p.m.).

The vehicles headways on the mainline of the freeway at the reversible-lane location exhibited an increase in both a.m. peak westbound direction and p.m. peak eastbound direction. The result of the K-S test indicated that the differences in the two cumulative distributions were statistically significant. It can be reasonably concluded that the headway increase, a positive effect, was a result of implementing the reversible-lane operation.

7.3.3 Location: I-75 and I-675, Saginaw and Bay Counties, Michigan

7.3.3.1 Comparison of Results for Vehicle Speeds

The team collected data at four locations on I-75—two within the work zone (in the reversible-lane configuration) and one each upstream and downstream (outside the work zone). Figure 55 illustrates the data collection locations.

Figure 56 illustrates the baseline traffic ADT volumes as well as the volumes carried by the work zone in the reversible-lane configuration for both northbound and southbound directions. The effect of a holiday weekend or recreational traffic was to significantly increase vehicles (>30,000) in the work zone, showcasing the capability of a reversible lane to change on demand. Figure 57 illustrates the hourly traffic volume changes and the capability of the reversible lane to handle these higher volumes.

Figure 55. Data collection locations.

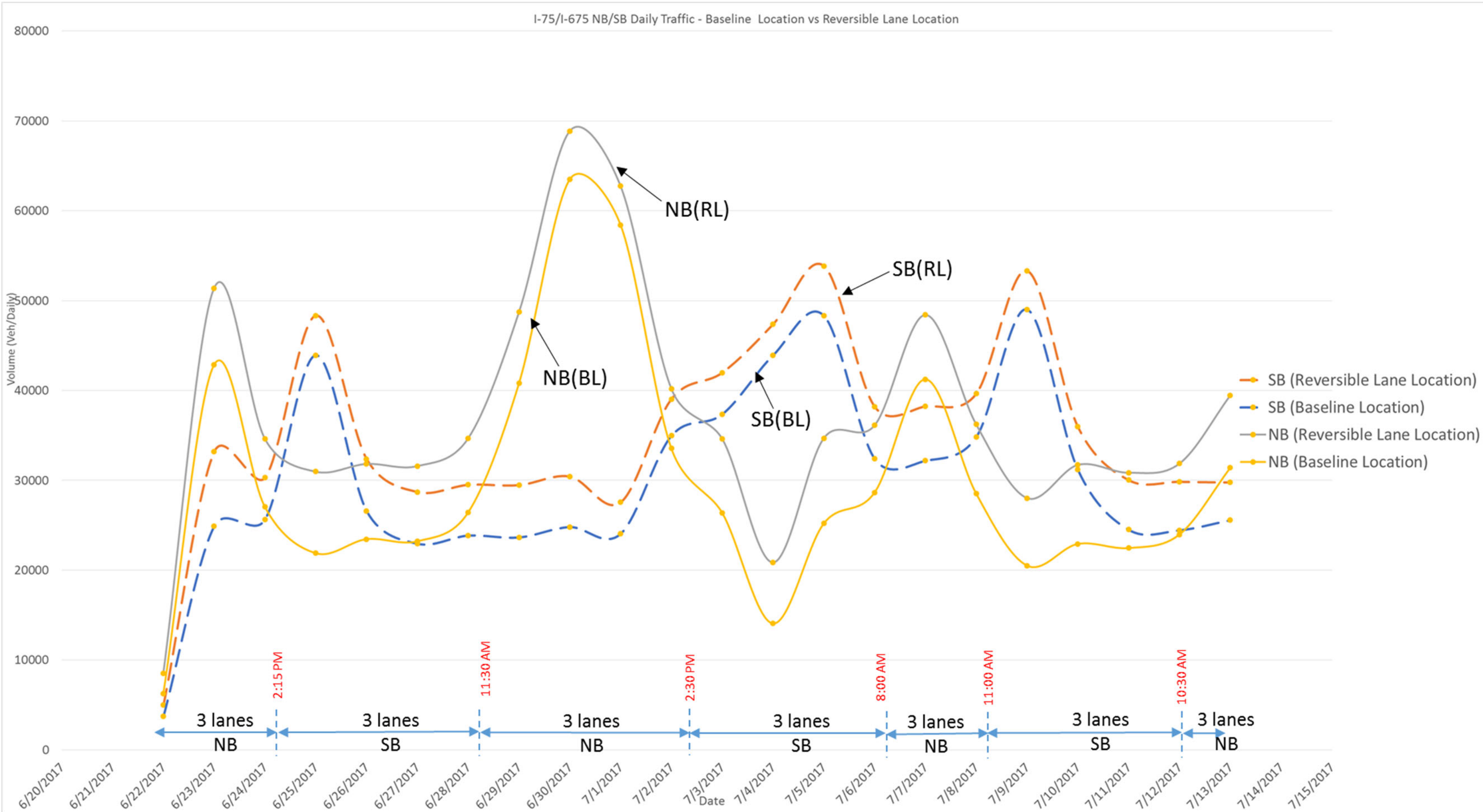


Figure 56. I-75 daily traffic volumes.

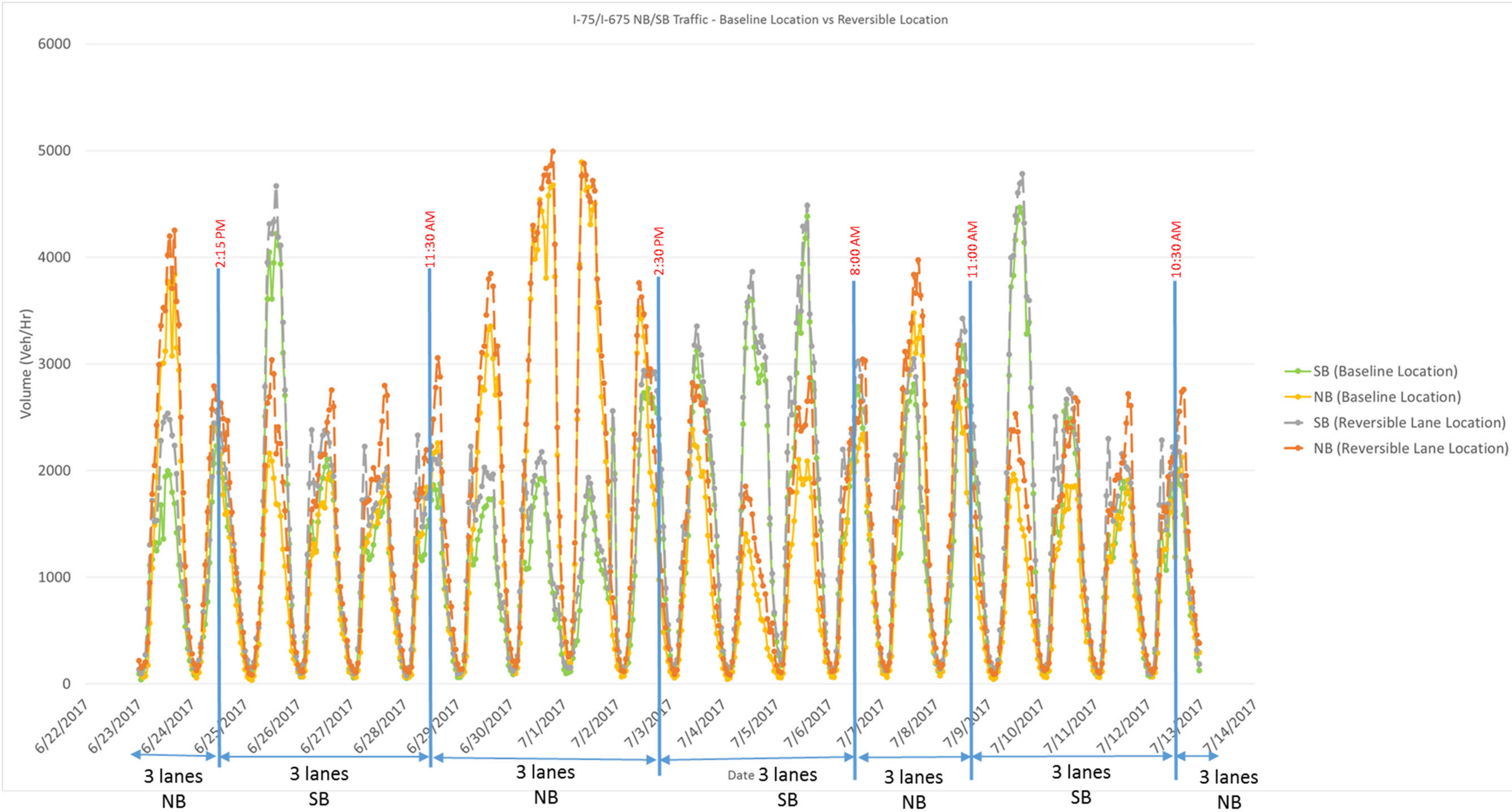


Figure 57. I-75 hourly traffic volumes.

Figures 58 and 59 illustrate the vehicle speeds and traffic volumes on the mainline for the northbound and southbound directions, respectively. The graphs indicated that I-75 did not have daily peaks; rather, a peak period spans the entire day from about 10:00 a.m. to 7:00 p.m., regardless of direction. In general, work zones will reduce capacity by at least 5% to 15% when the roadway is at or close to capacity due to narrow lanes or shoulders, barrier close to travel lane and other geometric changes. However, by implementing the reversible lane, it appears that capacity was maintained and vehicle speeds were within ±5% of baselines speeds.

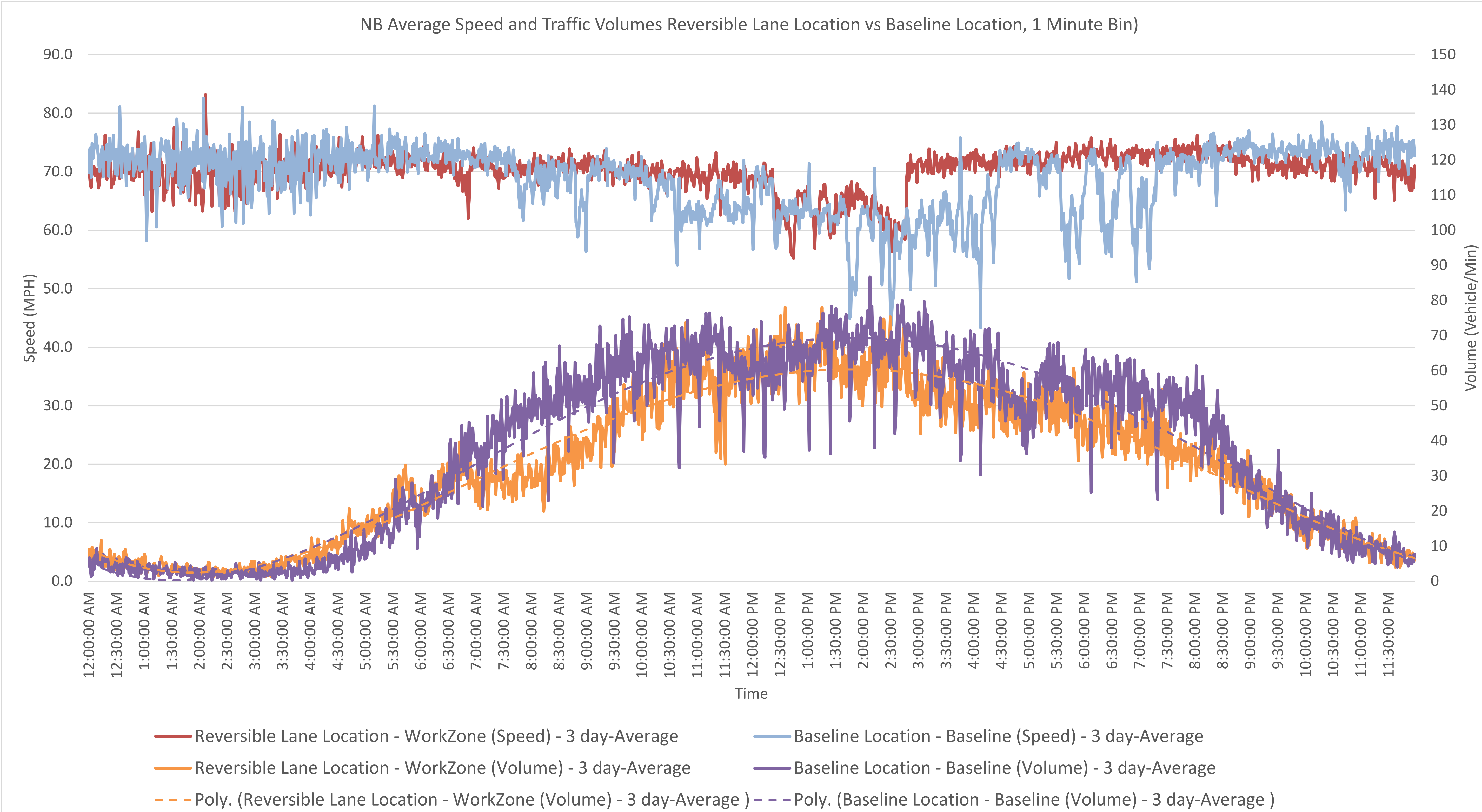


Figure 58. Northbound average speed and traffic volumes.

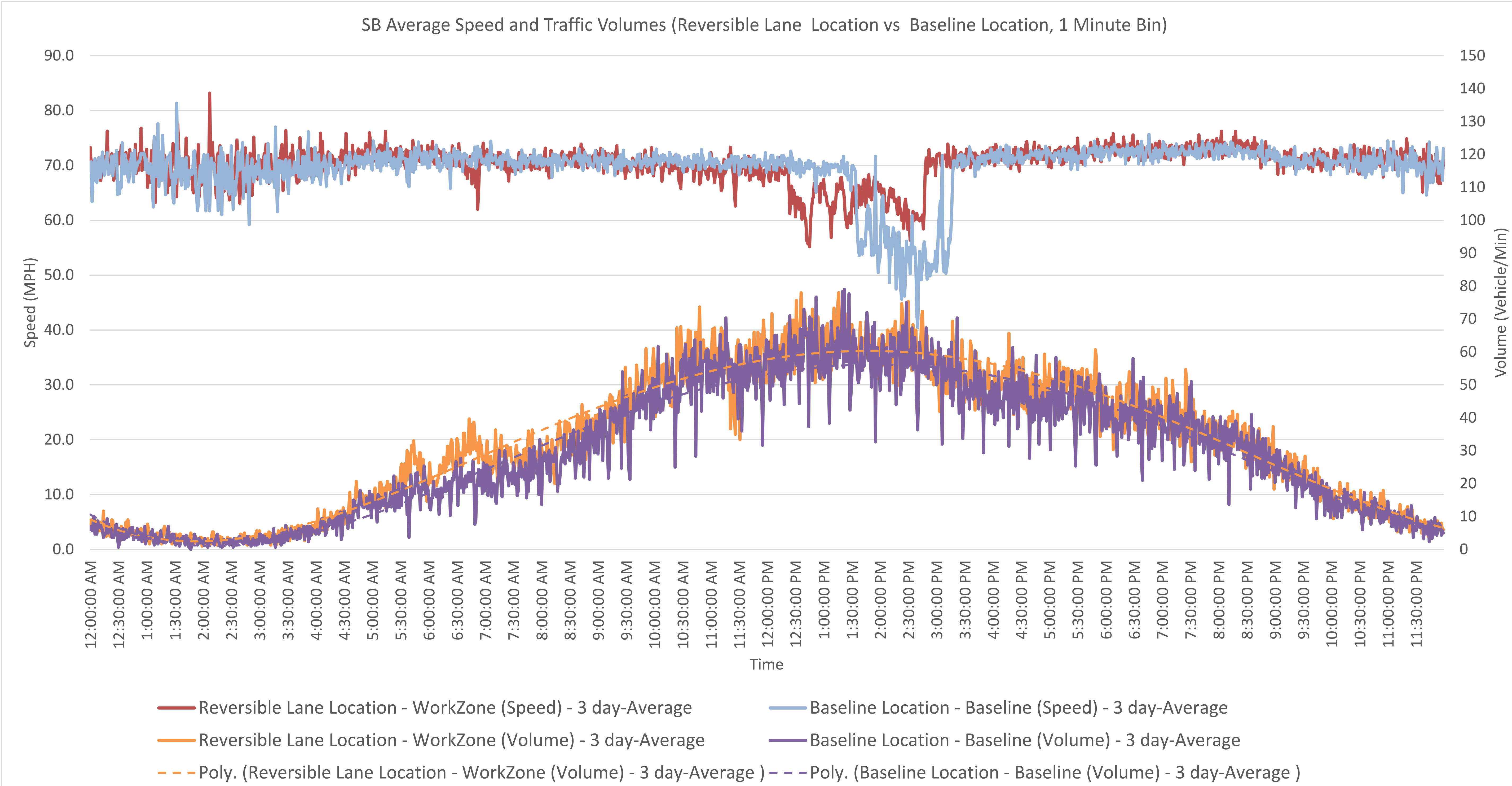


Figure 59. Southbound average speed and traffic volumes.

7.3.3.2 Statistical Analysis of Vehicle Speed

The team calculated changes in the mean speeds and 85th percentile speeds for vehicles between *with* and *without* implementing the reversible lane. Tables 55 and 56 show the comparison of mean speed and 85th percentile speed of vehicles on the freeway mainline and the statistical test results *with* and *without* the implementation of the reversible lane.

As Table 55 shows, the mean speeds of vehicles on the northbound mainline of the freeway increased for all time periods.

Table 55. Speed comparison—northbound direction baseline location vs. reversible-lane location.

Speed Comparison for NB I-75		Volume	Sample Size	Mean Speed (mph)	85th Percentile Speed (mph)	SD	Mean Speed t_{static}
1200-1300	Baseline	11134	523	64.71	73.00	9.55	**-10.17**
	Reversible Lane	11916	550	69.42	75.00	4.72	
1300-1400	Baseline	12071	523	61.15	73.00	11.89	**-12.55**
	Reversible Lane	12677	544	68.24	74.00	5.11	
1400-1500	Baseline	12251	524	59.22	73.00	12.13	**-11.86**
	Reversible Lane	13063	543	66.14	72.00	5.69	
1500-1600	Baseline	11169	528	62.69	76.00	14.90	**-8.84**
	Reversible Lane	12411	547	68.89	76.00	6.28	

(Bold indicates significance at the 95% confidence level, $\alpha = .05$)

The *t*-test results indicated the increases in mean speed during the periods of implementing the reversible lane were statistically significant for all time periods.

As Table 56 shows, the mean speeds of vehicles on the southbound mainline of the freeway increased for all time periods.

Table 56. Speed comparison—southbound direction baseline location vs. reversible-lane location.

Speed Comparison for SB I-75		Volume	Sample Size	Mean Speed (mph)	85th Percentile Speed (mph)	SD	Mean Speed t_{static}
1200-1300	Baseline	10670	534	69.25	74.00	4.18	-0.65
	Reversible Lane	11361	550	69.42	75.00	4.72	
1300-1400	Baseline	10655	528	64.50	74.00	13.68	**-5.89**
	Reversible Lane	11282	544	68.24	74.00	5.11	
1400-1500	Baseline	10339	531	56.75	74.00	20.12	**-10.36**
	Reversible Lane	10909	543	66.14	72.00	5.69	
1500-1600	Baseline	9025	531	67.26	75.00	11.56	**-2.86**
	Reversible Lane	9500	547	68.89	76.00	6.28	

(Bold indicates significance at the 95%confidence level, α = .05)

The *t*-test results indicated the increases in mean speed during the periods of implementing the reversible lane were statistically significant for time periods from 1:00 p.m. to 4:00 p.m.

After implementing the reversible lane, the speeds of vehicles on the mainline of the freeway increased in both northbound and southbound peak direction periods. Therefore, it seems that implementing the reversible lane had a positive effect.

7.3.3.3 Comparison of Results for Travel Time

Comparing the travel times through a work zone is a good MOE to determine the effect of the implementing reversible-lane operations. The reversible lane provides capacity to the mainline of the freeway and it is expected to maintain vehicle speeds, which will result in travel times similar to the baseline condition.

Figures 60 and 61 illustrate average 3-day travel times through the project limits for northbound and southbound peak direction periods, respectively. In general, travel times were maintained across the daily peak periods.

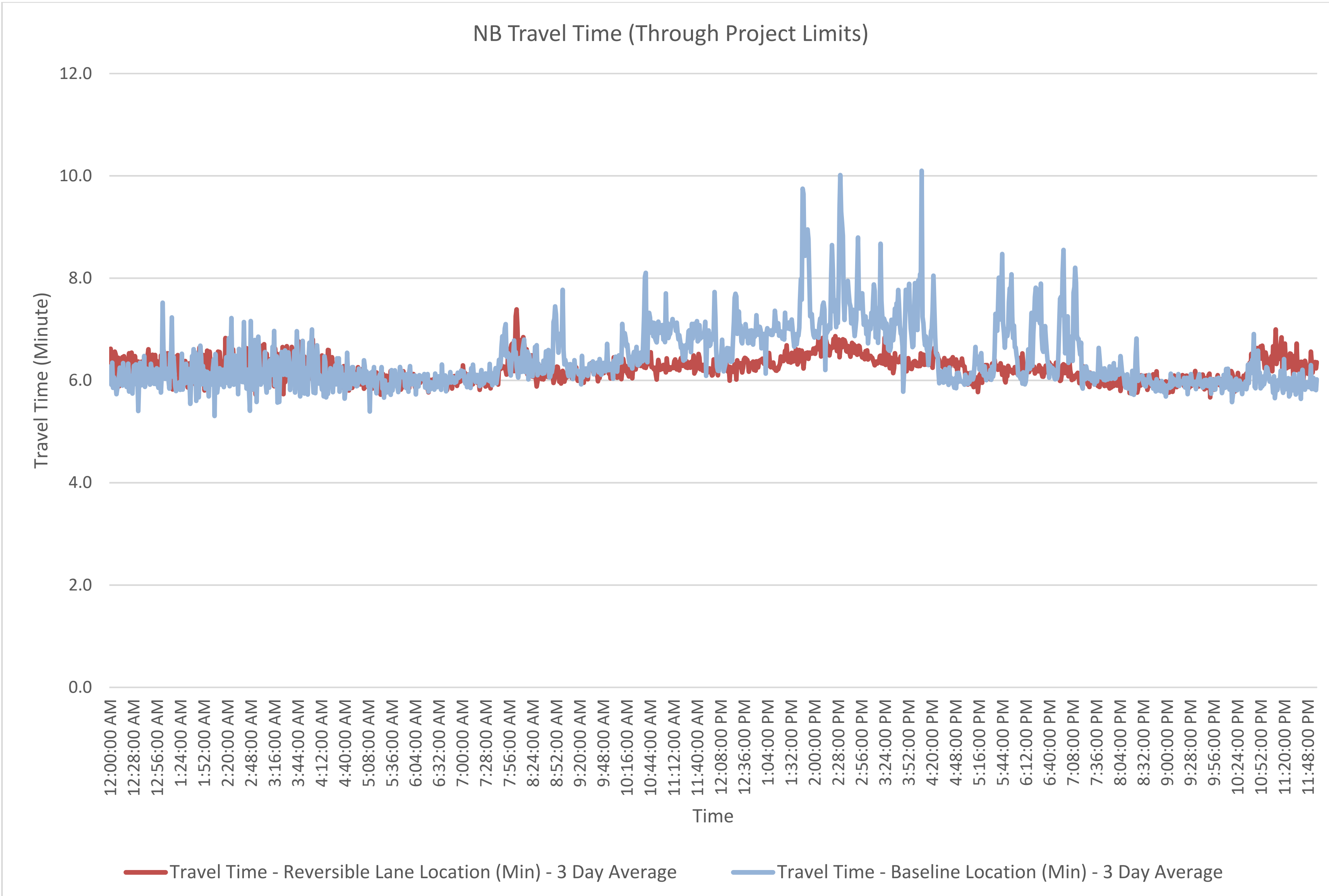


Figure 60. Northbound average travel time (distance: 7.3 mi).

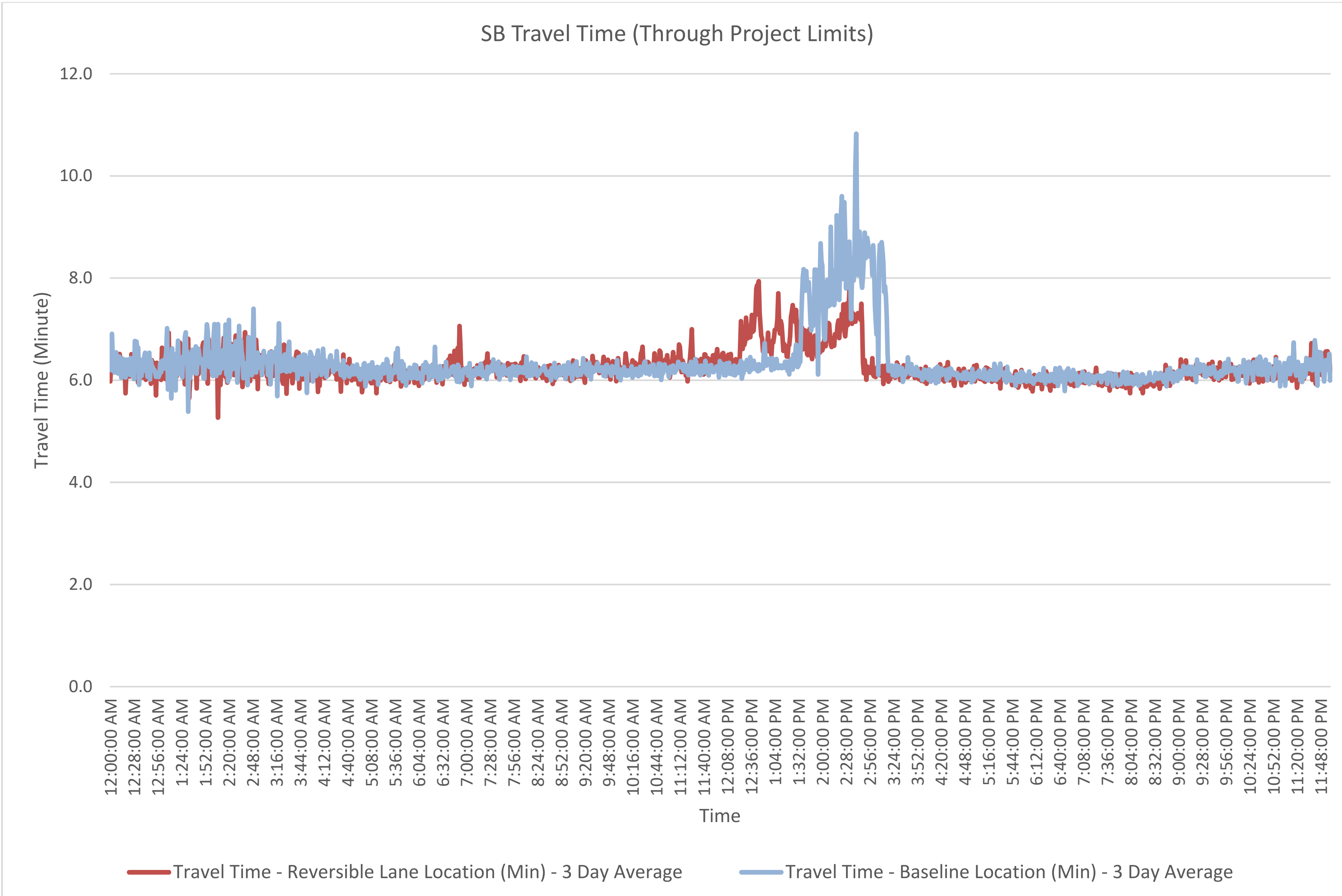


Figure 61. Southbound average travel time (distance: 7.3 mi).

7.3.3.4 Statistical Analysis of Travel Time

The team used a comparison of travel times to evaluate the effect of the reversible lane and determine if the reversible lane caused changes in travel characteristics. The team employed the *t*-statistic to evaluate the effect of implementing the reversible lane. The team calculated changes in average travel time and the 85th percentile travel time for vehicles traveling through the project limits between the *with* and *without* reversible lane implementation. Tables 57 and 58 show the comparison of average travel times and the 85th percentile travel time and the statistical test results *with* and *without* the reversible lane.

As Table 57 shows, the NB average travel time through the project limits decreased for all time periods. The *t*-test results indicated that decreases in travel time during the periods of implementing the reversible lane were statistically significant.

Table 57. Travel time comparison—northbound direction baseline location vs. reversible-lane location.

Travel Time Comparison for NB I-75		Volume	Sample Size	Average Travel Time (Min)	85th Percentile Travel Time (Min)	SD	Mean Travel Time t_{static}
1200-1300	Baseline	11134	180	6.85	8.24	1.28	**5.86**
	Reversible Lane	11916	180	6.28	6.50	0.23	
1300-1400	Baseline	12071	180	7.49	8.53	2.33	**6.15**
	Reversible Lane	12677	180	6.42	6.76	0.33	
1400-1500	Baseline	12251	180	7.83	9.20	2.26	**6.00**
	Reversible Lane	13063	180	6.73	7.07	0.95	
1500-1600	Baseline	11169	180	7.54	9.61	2.67	**5.68**
	Reversible Lane	12411	180	6.39	6.92	0.53	

(Bold indicates significance at the 95% confidence level, α = .05)

Table 58 shows that the SB average travel times in general were reduced. The *t*-test results indicated the decreases in travel time during the periods of implementing the reversible lane were statistically significant for all time periods from 12:00 p.m. to 4:00 p.m.

Table 58. Travel time comparison—southbound direction baseline location vs. reversible-lane location.

Travel Time Comparison for SB I-75		Volume	Sample Size	Average Travel Time (Min)	85th Percentile Travel Time (Min)	SD	Mean Travel Time t_{static}
1200-1300	Baseline	10670	180	6.26	6.46	0.22	**-5.55**
	Reversible Lane	11361	180	6.80	7.51	1.30	
1300-1400	Baseline	10655	180	7.45	6.91	3.65	**1.83**
	Reversible Lane	11282	180	6.92	8.15	1.27	
1400-1500	Baseline	10339	180	9.45	15.49	5.60	**5.83**
	Reversible Lane	10909	180	6.94	8.93	1.44	
1500-1600	Baseline	9025	180	6.87	6.45	2.41	**4.12**
	Reversible Lane	9500	180	6.13	6.33	0.19	

(Bold indicates significance at the 95% confidence level, α = .05)

After implementing the reversible lane, the travel times through project limits decreased in most of the time periods for both northbound and southbound peak direction periods. The travel time savings were similar and statistically significant. It can be reasonably concluded that improving travel time is the result of implementing the reversible lane. Therefore, implementing the reversible lane seems to have a positive effect on travel time.

7.3.3.5 Comparison of Results for Frequency of Headway

Headway is a good measure of congestion and lack of passing opportunities created by the traffic mix; it is also a good measure of safety as lane changing and frequent passing generally lead to conflicts and the likelihood of crashes. In general, a longer headway accepted by a merging vehicle is safer than a shorter headway.

The team examined the headways accepted by following vehicles to see if there were any differences between the *with* and *without* implementation of the reversible lane. The team conducted an analysis of headways of vehicles on the mainline of the freeway at the baseline location and the reversible-lane location to determine the average values and distribution for both northbound and southbound peak direction periods.

As mentioned, above, the team used the K-S test to judge how faithfully a distribution fits the sample data. The K-S test was adopted to determine the goodness-of-fit in the work zone traffic condition.

Table 59 summarizes the K-S test results of the northbound peak direction *vs. reversible-lane location.*

Table 59. K-S test results for the northbound peak direction period.

	Northbound Peak Direction Period	
	Baseline Location	Reversible-Lane Location
Sample Size	1,970	2,140
Mean Headway (seconds)	2.85	2.76
Median Headway (seconds)	2.61	2.50
Maximum difference (*D*)		0.03
Significance		No

Figure 62 presents a visual performance comparison of headway distributions through a cumulative distribution function in the peak hours (12:00 p.m. to 4:00 p.m.) at baseline and reversible-lane location. The team observed a slight shift in the headway distribution toward longer headway with the *with* reversible-lane condition compared to *without* the reversible-lane condition. The mean value of headway was 2.85 seconds at the *without* reversible-lane condition as opposed to 2.76 seconds at the *with* reversible-lane condition. With the significance level α of 0.05 and the sample size more than 40, the critical statistic of K-S test for the maximum difference between the cumulative distributions, *D*, was 0.04. The results of K-S test for (*without* reversible lane vs. *with* reversible lane) shows a value of D of 0.03 (less than the critical value of 0.04), which suggests the differences in the two cumulative distributions are not statistically significant.

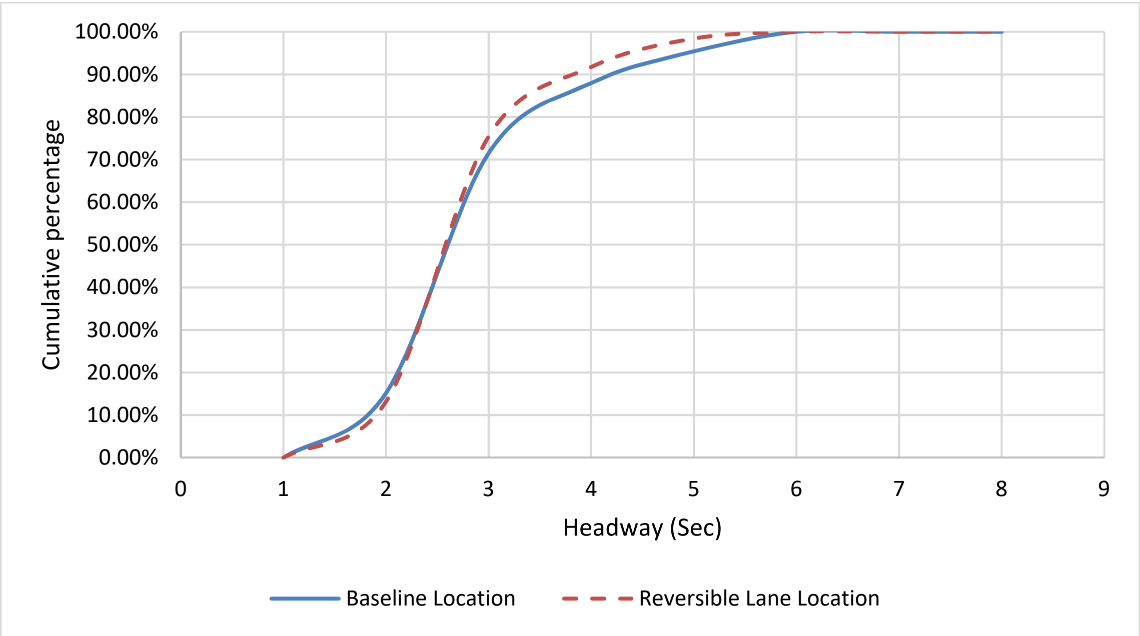


Figure 62. Cumulative headway distribution plot—northbound peak direction period—baseline location vs. reversible-lane location (12:00 p.m. to 4:00 p.m.).

Table 60 summarizes the K-S test results of the southbound peak direction *vs. reversible- lane location.*

Table 60. K-S test results for the southbound peak direction period.

	Southbound Peak Direction Period	
	Baseline Location	Reversible-Lane Location
Sample Size	1,905	2,056
Mean Headway (seconds)	3.31	3.25
Median Headway (seconds)	3.00	3.00
Maximum difference (*D*)		0.035
Significance		No

Figure 63 presents a visual performance comparison of headway distributions through a cumulative distribution function in the peak hours (12:00 p.m. to 4:00 p.m.) at baseline and reversible-lane location. The team observed a slight shift in the headway distribution toward shorter headway at reversible-lane location compared to baseline location. The mean value of headway was 3.31 seconds at baseline location as opposed to 3.25 seconds at reversible-lane location. With the significance level α of 0.05 and the sample size more than 40, the critical statistic of K-S test for the maximum difference between the cumulative distributions, *D*, is 0.04. The results of K-S test for (baseline location vs. reversible-lane location) shows a value of D of 0.035 (less than the critical value of 0.04), which suggests the differences in the two cumulative distributions are not statistically significant.

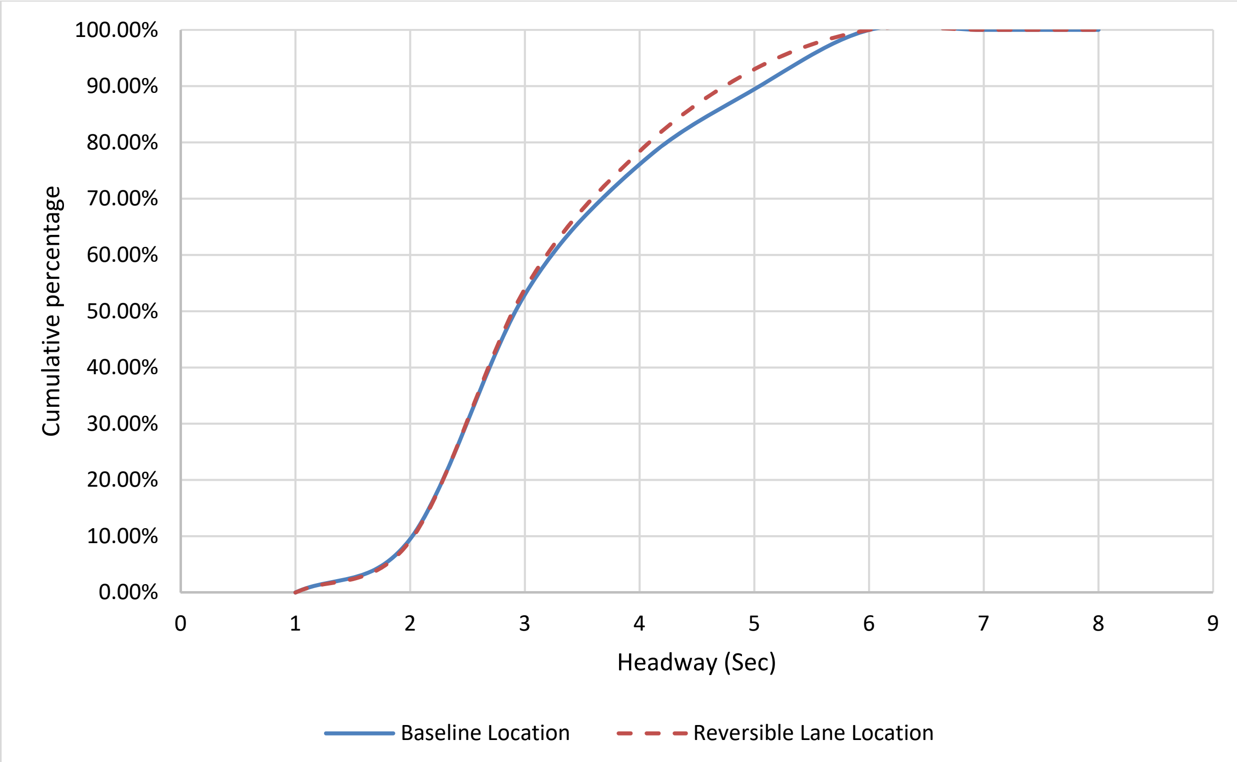


Figure 63. Cumulative headway distribution plot—southbound peak direction period—baseline location vs. reversible-lane location (12:00 p.m. to 4:00 p.m.).

The headways of vehicles on the mainline of the freeway at the reversible-lane location exhibited an increase in both northbound peak direction and southbound peak direction periods. The result of the K-S test indicated that the differences in the two cumulative distributions were not statistically significant.

7.4. Effects of Reversible Lane Operation on Traffic flow in Work Zones

All work zones at the three sites were considered long term and in place for more than four months. A concrete barrier separates the reversible lane from other lanes, which means that there was no potential for diversion to on and off ramps and almost no access to or from the work zone activities. The following discussion is an attempt to understand the relationship between a reversible-lane operation as part of the work zone strategy and traffic flow characteristics. Speed-flow graphs are shown followed by test site and for all lanes by direction. Note that the reversible lane (#3) is shown twice (i.e., by direction when changed over). The estimated volumes per lane in the work zones were significantly higher than that found using Highway Capacity Manual 2010 (HCM 2010), which ranged from 1500+ to 1700+. Capacity (Qmax) in the non-work zone condition ranged from 1,400 to 1,800 compared to the work zone where the range was between 1,600 to 2,250 vehicles per lane. In typical congested conditions, the work zone capacity is lower than non-work zone conditions; however, the data collected across all sites clearly demonstrated that using a reversible-lane configuration can maintain or increase the directional capacity, regardless of whether it supports daily (commuting) or weekday (holiday/recreational) traffic. The reversible lane in all lanes evaluated were separated from opposing traffic with concrete barriers. Figures 64–66 illustrate speed-flow characteristics by lane by direction for each test site (3—reversible lane, 2—center lane, 1—right lane).

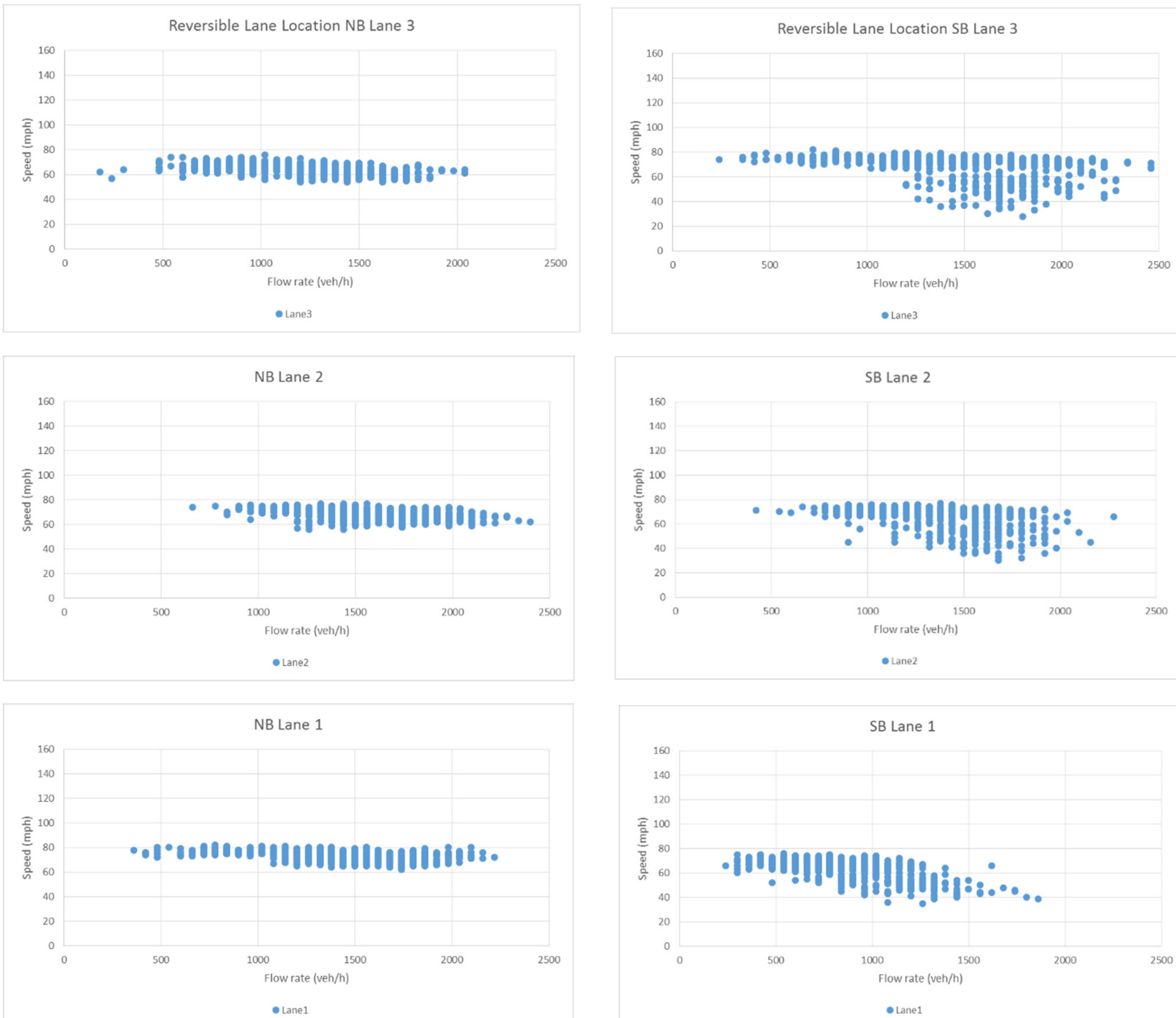


Figure 64. I-75 in Saginaw County, Michigan, speed-flow plots. Reversible-lane changeover took place during weekends and mid-week to accommodate recreational and holiday traffic.

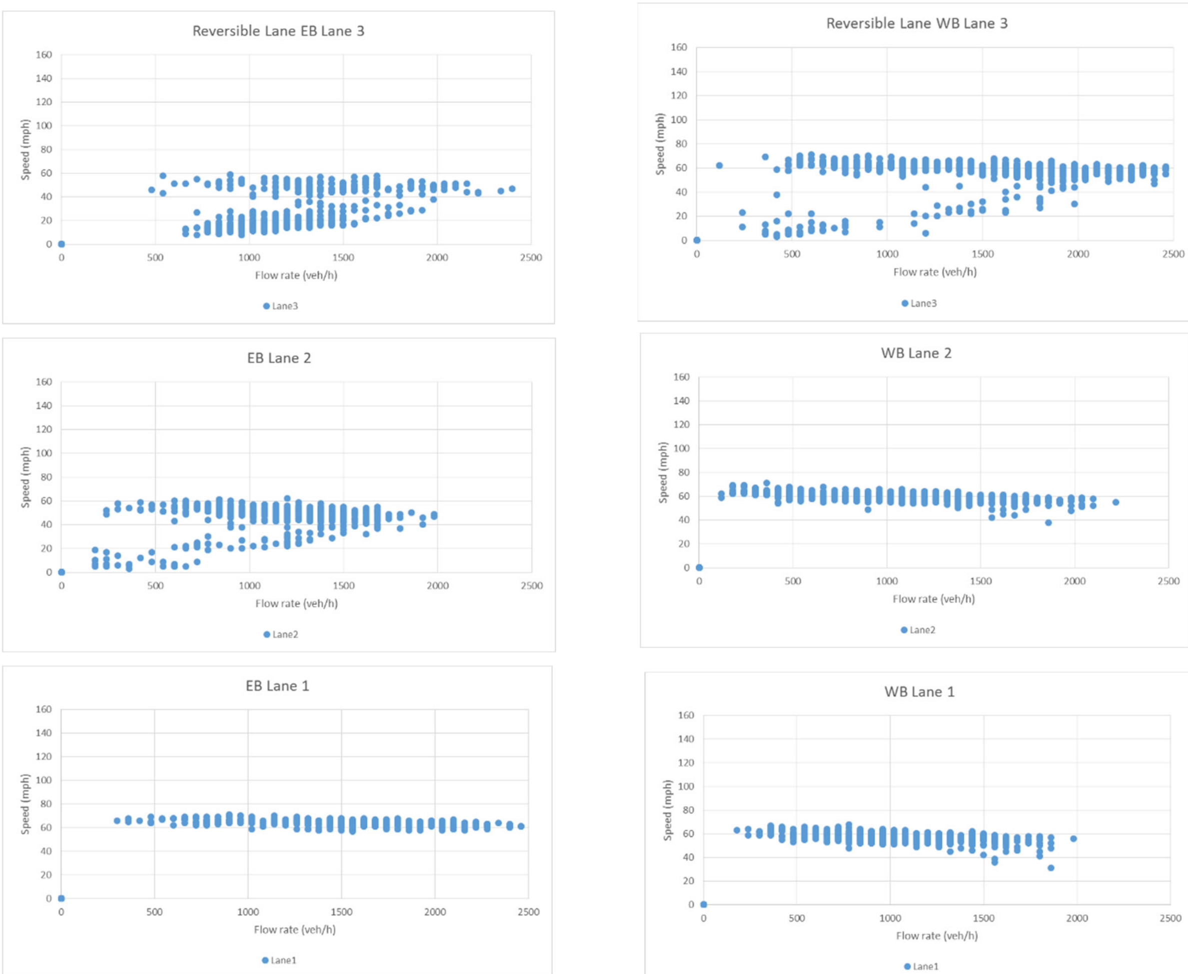


Figure 65. I-75 and I-675 in Saginaw and Bay Counties, Michigan, speed-flow plots. Reversible-lane changeover took place during weekends and mid-week to accommodate recreational and holiday traffic.

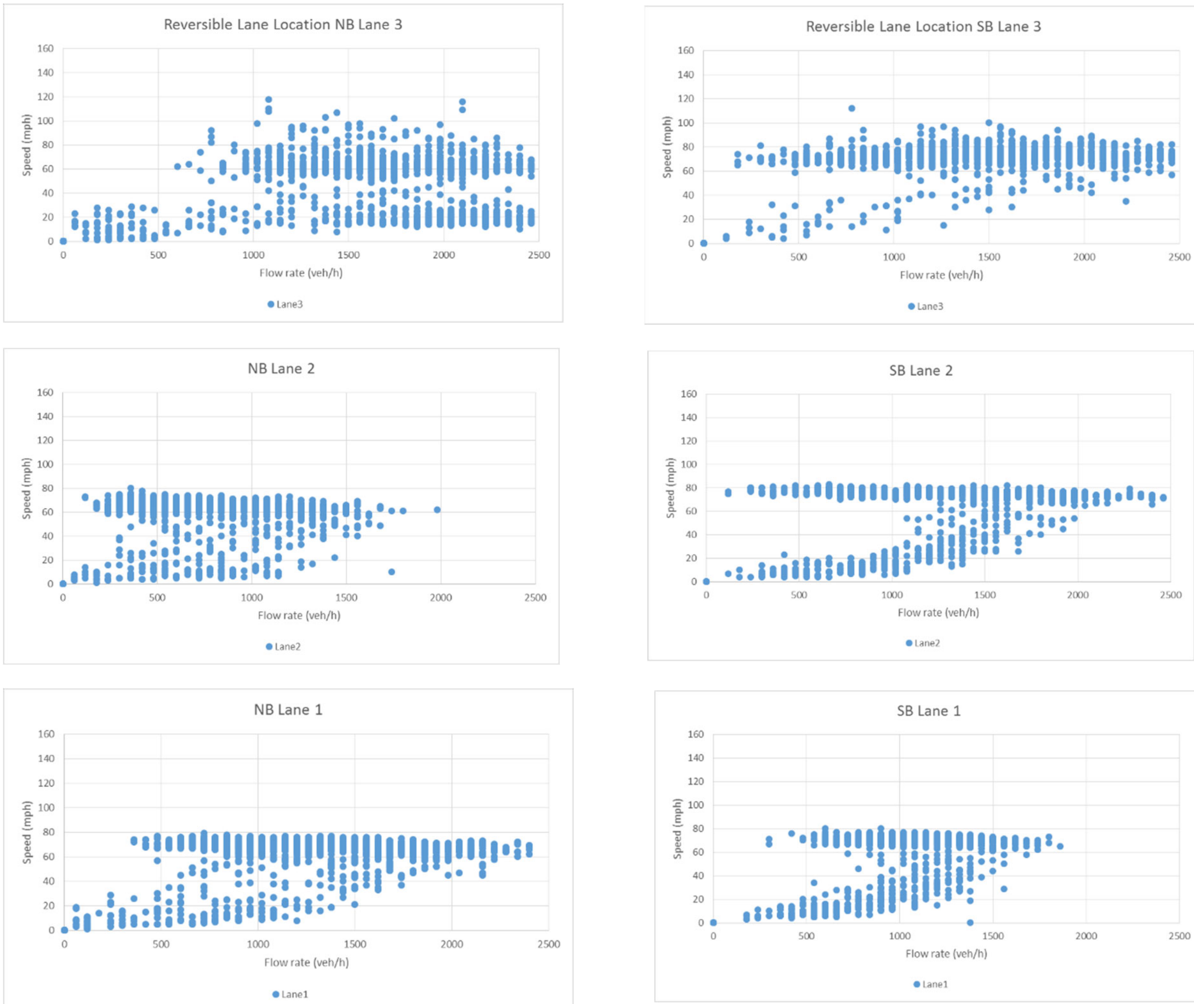


Figure 66. I-94 in Maplewood, Minnesota, speed-flow plots. Reversible-lane changeover took place after the morning peak period to accommodate afternoon commuting traffic.

7.5. Work Zone Crash Modification Factor for Reversible Lane

Table 61 shows the expected and actual crash results for deploying a reversible lane. The Total Hours column indicates the number of hours of data analyzed.

Table 61. Expected and actual crash results for reversible lane

Treatment	Total Hours	Expected Crashes	Actual Crashes	Percent Change
Reversible-Lane Deployment	6600	132.5	97	-27

For the reversible-lane condition, there was a 27% decrease from expected to actual crashes. In order to determine the proportional effects of the treatments on the numbers of crashes, an odds ratio analysis was undertaken according to the following equations:

$$CMF_D = \frac{TA_D TE_{ND} / TE_D TA_{ND}}{(1 + 1/TE_{ND} + 1/TE_D + 1/TA_{ND})}$$

$$SE(CMF_D) = \sqrt{\frac{CMF_D^2\,(1/TA_D + 1/TE_{ND} + 1/TE_D + 1/TA_{ND})}{(1 + 1/TE_{ND} + 1/TE_D + 1/TA_{ND})}}$$

Where:

CMF_D = crash modification factor = proportional effect of a deployment on crashes:

TA_D = total actual crashes during a deployment (equal to 97 in this case);

TE_D = total expected crashes during a deployment (equal to 132.5 in this case);

TA_{ND} = total actual crashes when nothing was deployed (equal to 81 in this case);

TE_{ND} = total expected crashes when nothing was deployed (equal to 117.1 in this case); and

SD (CMF_D) = standard error.

Table 62 shows the results from the CMF calculation. The calculated CMF for reversible lanes approximates 1, indicating that this treatment had no effect on reducing the number of crashes, without taking standard error into account.

Table 62. CMF results for reversible lane.

Treatment	CMF_D	$SE(CMF_D)$	ADT
Reversible Lane (Interstate)	1.029	0.200	Up to 100,000 Vehicles

The CMF is limited because of the few test sites. Agencies should only use this as a guide, monitor all work zones, and take appropriate action to mitigate any increase in crashes (i.e., severity and number). A general review of the data at these sites indicate that the upstream taper and the initial entry to the work zone appears to pose the most risk for drivers when in a reversible-lane configuration. Additional signing and pavement markings on the approach to the taper can help mitigate this issue.

8.0 Summary of Findings

8.1. Standalone Guidebook

Although there is a wealth of information, it is scattered among published research, DOT handbooks, manuals, plans, as well as unpublished documentation. This project developed a TPM Strategy Guidebook, published as *NCHRP Research Report 945*, that synthesizes useful knowledge from all these diverse sources to create a work zone guidebook. The guidebook provides a compendium of current knowledge on work zone strategies, including suggestions on when to use, benefits, effectiveness, technical issues, design requirements, state of the practice, and cost.

8.2. Field Evaluations Summary of Results

This section summarizes field evaluation findings, conclusions, and general considerations for future research. The summaries reference the appropriate NCHRP 03-111 sections: Section 5-Field Evaluations of Truck Lane Restrictions; Section 6-Field Evaluation of Temporary Ramp Metering; and Section 7-Field Evaluation of Reversible Lanes, respectively.

8.2.1 Field Evaluation of Truck Lane Restrictions

The team conducted field evaluations of the effectiveness of work zone truck lane restrictions on lane distribution and operations at three work zone sites in Michigan.

- **Lane Distribution of Trucks**. The primary interest in evaluating the effectiveness of truck lane restrictions was the percentage changes of the lane distribution of trucks at the test sites. The team compared the *without* and *with* percentages of lane distribution of trucks. All three sites restricted trucks to using the left lane and the data clearly show that the truck lane restrictions effectively created a tangible increase in the number of trucks using the left lane.
    - With the truck restrictions in place, the percentage change in trucks using the left lane, for all time periods, increased by 84.76% for SB I-75, 502.64% for SB US-23, and 669.04% for NB US-23. For all sites combined, the percentage change in trucks using the left lane, for all time periods, increased by 234.96%.
    - With truck restrictions in place, the percentage change in trucks using the right lane, for all time periods, decreased by 71.74% for SB I-75, 48.31% for SB US-23, and 51.32% for NB US-23. For all sites combined, the percentage change in trucks using the right lane, for all time periods, decreased by 59.36%.
- **Effect of Truck Lane Restrictions on Average Vehicle Speeds**. The team compared average vehicle speeds to determine if lane-use restrictions caused changes in vehicle

speeds. The vehicle speeds were compared separately according to the time period—morning peak period (6:00 to 9:00 a.m.), mid-day period (10:00 a.m. to 1:00 p.m.), and evening peak period (3:00 to 6:00 p.m.) for each site

- Average truck speeds were reduced in the right lane at two test sites and increased at the third test site. Average truck speeds increased in the left lane at one test site and decreased at two test sites.
- Average passenger car speeds were reduced in the right lane at two test sites and increased at a third test site. Average passenger car speeds increased in the left lane at one test site and decreased at two test sites.

Across the three study sites, the overall average truck speeds reduced by approximately 3 mph (5%) with the truck lane restrictions.

- **Effect on Frequency of Headway.** The comparisons of the headways of vehicles on the mainline left lane of the freeway during with and without conditions improved. Lower headways (less than 300 feet) improved between 19%–66%. Headways on the mainline right lane of the freeway saw no improvements but were greater than 300 feet.
- **Effect on Platoon Headways and Gap Acceptance.** The team examined the number of instances where a vehicle leads a platoon of traffic. A platoon is defined as a vehicle traveling with a headway greater than 3 seconds, followed by one or more vehicles with a headway less than 3 seconds. In this analysis, the team evaluated the headway for different vehicle leader–follower pairs (1) car followed by a car or truck (C-C and C-T) and (2) a truck followed by a car or truck (T-C and T-T). The team analyzed headways between vehicles to determine what changes, if any, occurred between the *with* and *without* periods. It was hypothesized that car drivers might feel impeded in the left lane because of the increase in the number of trucks and would try to pass slow-moving vehicles by moving into the right lane. The results showed that in the left lane, the headway for a truck following a car or truck increased and both groups decreased in the right lane. These results are in line with the hypothesis and did not substantiate the theory that the restrictions that would cause trucks to bear down on cars more frequently (i.e., restricting trucks to a particular lane decreases safety was not substantiated).
- Estimated cost to implement dedicated truck lanes is $15,000–$25,000 (static signs plus PCMS) over 5 mi.

Conditions most conducive to favorable application of truck lane restrictions are freeways with two or more lanes in each direction, interchanges spaced more than 2 to 3 mi apart, and with low ramp volumes and truck percentages between 10% to 25% of the total traffic stream.

Results also suggest that where crash data are available, transportation agencies conduct the *before*-and-*after* evaluations of the safety characteristics.

Compliance requires routine enforcement by regular traffic patrols or specialized dedicated truck-enforcement units. Agencies are encouraged to undertake a comprehensive public information campaign about the restriction and inform the public and the trucking community along the corridor to ensure success of the project.

8.2.2 Field Evaluation of Temporary Ramp Metering

The team used *with–without* ramp-metering studies to evaluate the effectiveness of ramp metering at the work zones on MN Route 52 in Rochester, Minnesota, and on I-279 in Ohio Township, Pennsylvania. The team implemented two ramp metering scenarios during the study period and evaluated fixed-cycle and variable-cycle lengths. The team also performed operational and driver behavior evaluations. The following paragraphs summarize the evaluation findings:

- The team compared vehicle speeds on the mainline of the freeway to evaluate the effect of implementing ramp metering. The results indicated that the speeds of vehicles on the mainline increased in both ramp-metering scenarios. The *t*-test results indicated the increases in mean speed in both ramp-metering scenarios were statistically significant and, thus, it can be reasonably concluded that implementing ramp metering seems to have a positive effect on vehicle speeds on the mainline. Overall, under saturated conditions, Fixed-cycle Length Ramp Metering performed slightly better than Variable-cycle Length Ramp Metering, with speed increases of 8.6 mph and 5.18 mph, respectively. When the mainline is less than 80% saturated, Variable-cycle Length Ramp Metering performed better than Fixed-cycle Length Ramp Metering with speed increases of 11–14 mph (right lane/left lane) and 5–8 mph (right lane/left lane), respectively. Left lane in each scenario experienced the larger increase as less vehicles attempt to merge.

- The team compared travel time through the work zones to determine the operational effect of implementing ramp metering. The results indicated that the travel time became shorter in both ramp-metering scenarios. The *t*-test results indicated the decreases in travel time in both ramp-metering scenarios are statistically significant and, thus, it can be reasonably concluded that implementing ramp metering seems to have a positive effect in travel time.

- The team also analyzed headways between vehicles on the mainline of the freeway at the merging area of ramp and mainline to determine the changes, if any, that occurred between *with* and *without* implementing ramp metering. The results were somewhat different for the two study areas, primarily because of roadway capacity condition.

  For MN Route 52 in Rochester, Minnesota, the results showed that headways of vehicles on the mainline increased in both ramp-metering scenarios (Fixed-cycle Length Ramp Metering = 2.42 seconds; Variable-cycle Length Ramp Metering = 2.44 seconds) from Meter-off scenario (2.3 seconds); however, the K-S test results indicated that the differences in the two cumulative distributions were not statistically significant. In general, the longer headway at the merging area is safer than a shorter headway.

  For I-279 in Ohio Township, Pennsylvania, the results showed that headways of vehicles on the mainline slightly decreased in both ramp-metering scenarios (from Meter-off scenario for both right lane and left lane). The K-S test results indicated that the differences in the two cumulative distributions were statistically significant for three scenario comparisons (Right lane–Meter-off vs. Variable-cycle Length; Right lane–Meter-off vs. Fixed-cycle Length; Left lane–Meter-off vs. Variable-cycle Length), and not statistically significant for one scenario-comparison (Right lane–Meter-off vs. Fixed-cycle). The reason for the decrease of headway on the I-279 project may resulted from the increase of the mainline traffic by approximately 10% to 20% that was directly related to implementing the ramp-metering strategy. Regardless, average headways were greater than 2.4 seconds across all time periods.

- Based on the observation of video for morning peak period (7:30 to 8:30 a.m.), the team determined that driver compliance rate for Variable-cycle Length Ramp Metering was higher than Fixed-cycle Length Ramp Metering and the compliance rate range was between 60% to 90%. This is considered good-to-excellent, as it was not accompanied by any type of enforcement.

- Once ramp metering is installed, it is estimated that the pay-off period will be approximately 3 to 5 months, depending on the level of congestion. (i.e., longer-term work zone greater than 5 months will yield significantly positive cost savings. Including crash costs and other savings would yield a shorter pay-off period.

Overall, this first evaluation of ramp metering in work zones during peak conditions proved very successful. The main lesson is to determine time of saturation and set the ramp metering at least 15–30 minutes prior. The traditional ramp-metering design volume criteria will not work in work zone conditions. Through this evaluation, the team recommends that the total lane/ramp vehicle volumes should not be greater than 1,600 vph (ramp volumes should not exceed 400–600 vph). An ideal traffic volume range would be closer to 1,400 combined vph per lane with the ramp volumes not to exceed 600 vehicles per hour for maximum effectiveness.

8.2.3 Field Evaluation of Reversible Lanes

The team used *with–without* reversible lane studies to evaluate the effectiveness of the reversible lane at work zones on three project sites. The team performed operational evaluations. The following is a summary of the evaluation findings:

- The team compared vehicle speeds on the mainline of the freeway to evaluate the effect of implementing the reversible lane. The results indicated that the speeds of vehicles on the mainline were generally maintained across all test sites.
- The team also compared travel time through work zone to determine the effect of implementing the reversible lane. The results indicated that the travel time became shorter in most of the time periods analyzed at three project sites. The *t*-test results indicated the decreases in travel time for most of the time periods analyzed were statistically significant. On average travel time improvements across all sites ranged from 5.6% to 15%. Thus, it can be reasonably concluded that implementing the reversible-lane operation seems to have a positive effect on travel time.
- The team analyzed headways between vehicles on the mainline of the freeway at the reversible-lane location and baseline location to determine the changes, if any, that occurred between *with* and *without* implementation of the reversible lane. The results showed that the headways in the reversible-lane configuration on a few occasions decreased because of the significant increase in traffic volumes; however, the minimum average headway was 2.7 seconds.
- Key to a successful reversible-lane operation is understanding the traffic flow pattern, daily and weekday, and knowing when to change over the lanes. Operation must be flexible enough to adjust to changes in demand.
- The reversible lane did not carry less traffic than other lanes—as previously thought—with a maximum traffic flow per lane from 1,600 to 2,250 vph.
- The capacity reduction factor for reversible-lane operation appeared to be 0.90 to 1.20; the latter occurred in cases where the reversible-lane operation was within barriers and not affected by ramps and other merging traffic.
- The number of crashes were higher when compared to a non-work zone condition, but less than expected for a work zone condition. Advanced signs and pavement markings on the approach to the taper can help enhance the operation of the reversible lane.

8.3. Suggestions for Future Research

The field evaluations conducted as part of this research effort are the first of their kind in a work zone setting and act as a good starting point for future research. Future research could add to the existing study by including work zones in different settings (congested, uncongested, rural, arterial freeways, etc.). Additional studies could also be used to validate the CMFs.

References

1. Ullman, G. L., M. Pratt, M. D. Fontaine, R. J. Porter, and J. Medina. *NCHRP Research Report 869: Estimating the Safety Effects of Work Zone Characteristics and Countermeasures: A Guidebook*. Transportation Research Board, Washington, D.C., 2018.

2. National Work Zone Safety Information Clearinghouse. *Work Zone Fatal Crashes and Fatalities*. The numbers for Fatal Crashes for Work Zone, Truck-Involved Work Zone, Pedestrian-Involved Work Zone come from the Fatality Analysis Reporting System, National Highway Traffic Safety Administration, U.S. Department of Transportation. The numbers for Work Zone Worker fatalities come from the Bureau of Labor Statistics, U.S. Department of Labor (https://www.workzonesafety.org/crash-information/work-zone-fatal-crashes-fatalities/#national, accessed on September 5, 2019).

3. Data shown is an estimate and comes from the General Estimates System (GES) and the Crash Report Sampling System (CRSS), National Highway Traffic Safety Administration, U.S. Department of Transportation. Values greater than 500 have been rounded to the nearest 1,000 and values less than 500 have been rounded to the nearest 100 to reflect the level of uncertainty that is associated with these estimates (https://www.workzonesafety.org/crash-information/work-zone-injuries-injury-property-damage-crashes/, accessed on September 5, 2019).

4. FHWA Work Zone Facts and Statistics (https://ops.fhwa.dot.gov/wz/resources/facts_stats.htm#ftn5, accessed on September 5, 2019)

Appendix A—Survey Form

NCHRP 03-111

Effectiveness of Work Zone Transportation Management Plan (TMP) Strategies

Survey — Part A

Contents

1 Introduction

The National Academy of Sciences (NAS), through the Transportation Research Board (TRB), conducts studies relating to contemporary transportation issues. In 1963, the TRB established the National Cooperative Highway Research Program (NCHRP) to administer research projects deemed critical by the American Association of State Highway and Transportation Officials (AASHTO) Standing Committee on Research to the needs of state DOTs.

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A. **Part A** relates to 'Transportation Operations (TO)' strategies and 'Temporary Traffic Control (TTC)' strategies. TO and TTC strategies are further sub-divided into various categories:
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   iv. TO—Traffic/incident management and enforcement strategies
   v. TTC—Control strategies
   vi. TTC—Traffic control devices
   vii. ICS—Intermodal Control Strategies

B. **Part B** relates to the 'Public Information' strategies, which is sub-divided into 'Public Awareness' and 'Motorist Information' strategies.

C. **Part C** relates to 'Project Coordination & Innovative Construction Strategies'.

The expected outcome of the project will be a Guidebook to help work zone practitioners identify and select the most effective and cost-efficient TMP strategies to implement in a particular construction setting on future projects.

KLS Engineering, LLC is conducting this research under contract to NCHRP. Surveys have been sent to all state DOTs and selected local governments. If you have any questions about this survey or how the data will be used please contact the Principal Investigator, Leverson Boodlal at e-mail leverson.boodlal@kls-eng.com. **A copy of the Guidebook will be mailed to you once the project is completed.**

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	Contact No. 1	Contact No. 2
Name		
Phone Number		
Email		

This survey can also be completed via a conference call. Please email leverson.boodlal@kls-eng.com, if conference call is your preferred method.

All data obtained from participants will be kept confidential and will only be reported in an aggregate format.

THANK YOU IN ADVANCE FOR YOUR HELP AND COOPERATION WITH THIS PROJECT!

2 General

1. Do you have any documented work zone TMP examples (significant project) that could be shared with other agencies or explored in greater detail as a case study?

   - ☐ Yes
     - ☐ Describe ____ ____(or)
     - ☐ Provide Web link ______________________________________ (or)
     - ☐ Upload file (*the electronic version of this survey provides options to upload a maximum of two files*)______________________________ (or)
     - ☐ Don't have information readily available, contact me later
     - ☐ Contact Mr./Ms.:____________________________________ at phone/email: ____________________________________
   - ☐ No

2. Does your agency undertake work zone audits? Please provide as much information as possible.

   - ☐ Yes (please select applicable criterion from table below).
   - ☐ No

Stage of Audit	Responsible Agency	Applicable Roadways	Frequency of Use	Effectiveness
☐ Construction stage	☐ FHWA ☐ In-house (local, statewide) ☐ External consultant/ contractor	**Check all that apply:** ☐ Interstate ☐ Other Freeways/ Expressways ☐Arterials ☐ Collectors ☐ All Roads	**Check one:** ☐ Selective to particular project type ☐ Very Frequent ☐ Frequent ☐ Rarely Used ☐ Not Used ☐ Other	**Check one:** ☐ Very Effective ☐ Somewhat Effective ☐ Not Effective ☐ Inconclusive ☐ Don't Know
☐Post-construction stage (to examine effectiveness of implemented measures)	☐FHWA ☐ In-house (local, statewide) ☐ External consultant/ contractor	**Check all that apply:** ☐Interstate ☐ Other Freeways/ Expressways ☐Arterials ☐ Collectors ☐ All Roads	**Check one:** ☐ Selective to particular project type ☐ Very Frequent ☐ Frequent ☐ Rarely Used ☐ Not Used Other	**Check one:** ☐ Very Effective ☐ Somewhat Effective ☐ Not Effective ☐ Inconclusive Don't Know

____

3. If available, please upload the latest work zone audit.

- ☐ Yes
  - ☐ Describe ____
    ____(or)
  - ☐ Provide Web link ____ (or)
  - ☐ Upload file (*the electronic version of this survey provides options to upload a maximum of two files*)____ (or)
  - ☐ Don't have information readily available, contact me later
  - ☐ Contact Mr./Ms.:____
    at phone/email: ____
- ☐ No

4. Is design for significant projects prepared through (check all that apply):
   - ☐ Central Office
   - ☐ District Office
   - ☐ Other, explain: ____
     ____

5. Is Construction Management for significant projects prepared through (check all that apply):
   - ☐ Central Office
   - ☐ District Office
   - ☐ Other, explain: ____
     ____

6. Is work zone project review for significant projects prepared through (check all that apply):
   - ☐ Central Office
   - ☐ District Office
   - ☐ Site Project Personnel
   - ☐ Other, explain: ____
     ____

2.1 Work Zone Performance Measures

7. Has your agency established performance measures specifically designed to monitor congestion and delays in work zones (project specific)?

   ☐ Yes

   ☐ Describe ____
   ____(or)

   ☐ Provide Web link ____ (or)

   ☐ Upload file (*the electronic version of this survey provides options to upload a maximum of two files*)____ (or)

   ☐ Don't have information readily available, contact me later

   ☐ Contact Mr./Ms.:____
   at phone/email: ____

   ☐ No

8. Has your agency established performance measures specifically to monitor safety in work zones e.g. work zone crash rate/project?

   ☐ Yes

   ☐ Describe ____
   ____(or)

   ☐ Provide Web link ____ (or)

   ☐ Upload file (*the electronic version of this survey provides options to upload a maximum of two files*)____ (or)

   ☐ Don't have information readily available, contact me later

   ☐ Contact Mr./Ms.:____
   at phone/email: ____

   ☐ No

9. What software tools does your agency use to analyze anticipated work zone impacts including detouring of traffic? List by order of preference.

   ☐ Tool #1: ___________________ Is this tool specific to your DOT? ☐Yes ☐No

   ☐ Tool #2: ___________________ Is this tool specific to your DOT? ☐Yes ☐No

   ☐ Tool #3: ___________________ Is this tool specific to your DOT? ☐Yes ☐No

____

10. Does your agency have any projects where you collected traffic and/or safety data related to the implementations of traffic management work zone strategies that you can share with the research team for possible evaluations? If so please describe:

    Describe: ____
    ____
    ____

3 Transportation Operations (TO) Strategies

DOTs use transportation operations (TO) strategies to mitigate work zone impacts and improve transportation operations and management of the transportation system. TO strategies typically include:

i. TO—Demand management strategies
ii. TO—Corridor/network management (traffic operations) strategies
iii. TO—Work zone safety management strategies
iv. TO—Traffic/incident management and enforcement strategies
v. TTC—Control strategies
vi. TCD—Traffic control device
vii. ICS—Intermodal Control Strategies

3.1 Demand Management Strategies

Demand management strategies include a wide range of techniques intended to reduce the volume of traffic traveling through the work zone; these techniques can include such means as diverting travelers to alternate modes, shifting trips to off-peak hours, or shifting vehicles to alternate routes.

11. Which demand management strategies has your agency used and what is your experience using them? Please select from list below and provide as much information as possible.

Demand Management Strategy List	**Frequency of Use** (1=Selective to a particular project, 2=Frequently, 3=Limited, 4=Don't Know, 5=Not Used)	**Roadways mainly used on** (1=Interstates/Freeways, 2=Arterials, 3=Both)	**Rate Effectiveness** (1=Highly Effective, 2=Moderately Effective, 3=Not Effective, 4=Inconclusive, 5=Don't Know)	**Rate Public Feedback Response (if known)** (1=Very Good, 2=Good, 3=Satisfactory, 4=Poor, 5=Very Poor, 6=Don't Know)
☐Transit service improvements				
☐Transit incentives				
☐Shuttle Services				
☐Ridesharing/carpooling incentives				
☐Park-and-ride promotion				
☐High-occupancy vehicle (HOV) lanes				
☐Toll/congestion pricing				
☐Variable work hours				
☐Telecommuting				

___

12. Please identify up to two (2) major road construction projects that deployed significant demand management strategies (if available).

	Project Name	Demand Management Strategy Used
1		
2		

13. From the demand management strategies selected in Question #11, has your agency conducted any in-house research, before-after studies, field trials, etc. (either published or unpublished, such as internal memo)?

 - ☐ Yes
   - ☐ Describe ____ ____(or)
   - ☐ Provide Web link ____ (or)
   - ☐ Upload file (*the electronic version of this survey provides options to upload a maximum of two files*)____ (or)
   - ☐ Don't have information readily available, contact me later
   - ☐ Contact Mr./Ms.:____ at phone/email: ____
 - ☐ No

14. Has your agency used demand management strategies different than the ones listed in Question #11? If so, please describe them.

 Describe:____
 ____
 ____

15. Which demand management strategies would you like to see evaluated? List two only and explain why.

 Describe:____
 ____
 ____

3.2 Corridor/Network Management Strategies

This category includes using various traffic operations techniques and technologies strategies to optimize traffic flow through the work zone corridor and adjacent roadways.

16. Which corridor/network management strategies has your agency used and what is your experience using them? Please select from list below and provide as much information as possible.

Corridor/Network Management Strategy List	**Frequency of Use** (1=Selective to a particular project, 2=Frequently, 3=Limited, 4=Don't Know, 5=Not Used)	**Roadways mainly used on** (1=Interstates/Free ways, 2=Arterials, 3=Both)	**Rate Effectiveness** (1=Highly Effective, 2=Moderately Effective, 3=Not Effective, 4=Inconclusive, 5=Don't Know)	**Rate Public Feedback Response (if known)** (1=Very Good, 2=Good, 3=Satisfactory, 4=Poor, 5=Very Poor, 6=Don't Know)
☐ Street/intersection Improvements	☐	☐		☐
☐ Truck/heavy vehicle restrictions	☐	☐		☐
☐ Separate truck lanes	☐	☐		☐
☐ Reversible lanes	☐	☐		☐
☐ Dynamic lane closure system	☐	☐		☐
☐ Ramp metering	☐	☐		☐
☐ Temporary suspension of ramp metering	☐	☐		☐

17. Please provide up to two (2) major road construction projects that deployed significant corridor/network management strategies (if available).

	Project Name	**Corridor/Network Management Strategy Used**
1		
2		

18. From the corridor/network management strategies selected in Question #16, has your agency conducted any in-house research, before-after studies, field trials, etc. (either published or unpublished such as internal memo)?

☐ Yes

☐ Describe ____
____(or)

☐ Provide Web link ____ (or)

- ☐ Upload file (*the electronic version of this survey provides options to upload a maximum of two files*)____ (or)
- ☐ Don't have information readily available, contact me later
- ☐ Contact Mr./Ms.:____ at phone/email: ____

☐ No

19. Has your agency used corridor/network management strategies different than the ones listed in Question #16? If so, please describe them.

    Describe:____
    ____
    ____

20. Which corridor/network management strategies would you like to see evaluated? List two only and explain why.

    Describe:____
    ____
    ____

3.3 Work Zone Safety Management Strategies

This category includes devices, features, and management procedures used to address traffic safety concerns in work zones.

21. Which work zone safety management strategies has your agency used and what is your experience using them? Please select from list below and provide as much information as possible.

Work Zone Safety Management Strategy List	**Frequency of Use** (1=Selective to a particular project, 2=Frequently, 3=Limited, 4=Don't Know, 5=Not Used)	**Roadways mainly used on** (1=Interstates/Freeways, 2=Arterials, 3=Both)	**Rate Effectiveness** (1=Highly Effective, 2=Moderately Effective, 3=Not Effective, 4=Inconclusive, 5=Don't Know)	**Rate Public Feedback Response (if known)** (1=Very Good, 2=Good, 3=Satisfactory, 4=Poor, 5=Very Poor, 6=Don't Know)
☐ Speed limit reduction	☐	☐		☐
☐Variable speed limits	☐	☐		☐
☐Movable traffic barrier systems	☐	☐		☐
☐Positive Protection	☐	☐		☐
☐Temporary rumble strips	☐	☐		☐
☐Intrusion alarms	☐	☐		☐
☐Warning lights	☐	☐		☐
☐Automated Flagger Assistance Devices AFAD)	☐	☐		☐
☐TMP monitor/ inspection team	☐	☐		☐

22. Please provide up to two (2) major road construction projects that deployed work zone safety management strategies (if available)

	Project Name	**Work Zone Safety Management Strategy Used**
1		
2		

23. From the work zone safety management strategies selected in Question #21, has your agency conducted any in-house research, before-after studies, field trials, etc. (either published or unpublished such as internal memo)?

____

- ☐ Yes
  - ☐ Describe ____
    ____(or)
  - ☐ Provide Web link ____ (or)
  - ☐ Upload file (*the electronic version of this survey provides options to upload a maximum of two files*)____ (or)
  - ☐ Don't have information readily available, contact me later
  - ☐ Contact Mr./Ms.:____
    at phone/email: ____
- ☐ No

24. Has your agency used work zone safety management strategies different than the ones listed in Question #21? If so, please describe them.

    Describe:____
    ____
    ____

25. Which work zone safety management strategies would you like to see evaluated? List two only and explain why.

    Describe:____
    ____
    ____

3.4 Traffic/Incident Management and Enforcement Strategies

This category includes various strategies to manage work zone traffic operations. Work zone traffic management strategies monitor traffic conditions and make adjustments to traffic operations based on changing conditions including related incidents (e.g., crashes). These strategies involve improved detection, verification, response, quick clearance of crashes, and other incidents in work zones and on detour routes. This category also includes strategies to provide adequate enforcement of traffic regulations in work zones.

26. Which traffic/incident management and enforcement strategies has your agency used and what is your experience using them? Please select from list below and provide as much information as possible.

Traffic/Incident Management and Enforcement Strategy List	**Frequency of Use** (1=Selective to a particular project, 2=Frequently, 3=Limited, 4=Don't Know, 5=Not Used)	**Roadways mainly used on** (1=Interstates/Freeways, 2=Arterials, 3=Both)	**Rate Effectiveness** (1=Highly Effective, 2=Moderately Effective, 3=Not Effective, 4=Inconclusive, 5=Don't Know)	**Rate Public Feedback Response (if known)** (1=Very Good, 2=Good, 3=Satisfactory, 4=Poor, 5=Very Poor, 6=Don't Know)
☐ ITS for traffic monitoring/management (project specific)	☐	☐		☐
☐ITS for detouring traffic (project specific)				
☐Surveillance [Closed-Circuit Television (CCTV), loop detectors, lasers, probe vehicles] (project specific)				
☐Helicopter for aerial surveillance				
☐Reference Location Signs (aka mile markers)				
☐Tow/freeway service patrol				
☐Contract support for incident management				
☐Incident/emergency management coordinator				
☐Incident/emergency response plan				
☐Dedicated (paid) police enforcement				
☐Cooperative police enforcement				
☐Automated enforcement				
☐Increased penalties for work zone violations				

____

Traffic/Incident Management and Enforcement Strategy List	**Frequency of Use** (1=Selective to a particular project, 2=Frequently, 3=Limited, 4=Don't Know, 5=Not Used)	**Roadways mainly used on** (1=Interstates/Freeways, 2=Arterials, 3=Both)	**Rate Effectiveness** (1=Highly Effective, 2=Moderately Effective, 3=Not Effective, 4=Inconclusive, 5=Don't Know)	**Rate Public Feedback Response (if known)** (1=Very Good, 2=Good, 3=Satisfactory, 4=Poor, 5=Very Poor, 6=Don't Know)
☐Queue Warning System				

27. Please provide up to two (2) major road construction projects that deployed traffic/incident management and enforcement strategies (if available)

	Project Name	Traffic/Incident Management and Enforcement Strategy Used
1		
2		

28. From the traffic/incident management and enforcement strategies selected in Question #26, has your agency conducted any in-house research, before-after studies, field trials, etc. (either published or unpublished such as internal memo)?

☐ Yes

☐ Describe ____
____(or)

☐ Provide Web link ____ (or)

☐ Upload file (*the electronic version of this survey provides options to upload a maximum of two files*)____ (or)

☐ Don't have information readily available, contact me later

☐ Contact Mr./Ms.:____
at phone/email: ____

☐ No

29. Has your agency used traffic/incident management strategies different than the ones listed in Question #26? If so, please describe them.
Describe:____
____
____

30. Which traffic/incident management and enforcement strategies would you like to see evaluated? List two only and explain why.

Describe:____
____
____

4 Temporary Traffic Control (TTC)

Transportation agencies use temporary traffic control (TTC) strategies, devices, and contracting/construction techniques and coordination to facilitate traffic flow safely through and around work zones.

4.1 Control Strategies

This category includes using various traffic control approaches to accommodate road users within the work zone or the adjoining corridor in an efficient and safe manner, while providing adequate access to the roadway to perform the required construction, maintenance, or utility work.

31. Which control strategies has your agency used and what is your experience using them? Please select from list below and provide as much information as possible.

Control Strategy List	**Frequency of Use** (1=Selective to a particular project, 2=Frequently, 3=Limited, 4=Don't Know, 5=Not Used)	**Roadways mainly used on** (1=Interstates/Freeways, 2=Arterials, 3=Both)	**Rate Effectiveness** (1=Highly Effective, 2=Moderately Effective, 3=Not Effective, 4=Inconclusive, 5=Don't Know)	**Rate Public Feedback Response (if known)** (1=Very Good, 2=Good, 3=Satisfactory, 4=Poor, 5=Very Poor, 6=Don't Know)
☐ Full roadway closures				
☐ Two-way traffic on one side of divided facility (crossover)				
☐ Reversible lanes				
☐ Night work				
☐ Weekend work				
☐ Offsite detours/use of alternate routes				

32. Please provide up to two (2) major road construction projects that deployed control strategies.

	Project Name	**Control Strategy Used**
1		
2		

33. From the control strategies selected in Question #31, has your agency conducted any in-house research, before-after studies, field trials, etc. (either published or unpublished such as internal memo)?

☐ Yes

☐ Describe ____
____(or)

☐ Provide Web link ______________________________________ (or)

- ☐ Upload file (*the electronic version of this survey provides options to upload a maximum of two files*)____ (or)
- ☐ Don't have information readily available, contact me later
- ☐ Contact Mr./Ms.:____
at phone/email: ____

☐ No

34. Which control strategies would you like to see formally evaluated? List two only and explain why.

Describe:____
____
____

4.2 Traffic Control Devices (TCD)

The Manual on Uniform Traffic Control Devices (MUTCD) provides standards, guidelines, and other information pertaining to installing, maintaining, and operating Temporary Traffic Control Devices on roadways.

35. This section is to determine if your agency has conducted any research within last 10 years on TCDs that required interim approval permission by the FHWA, such as new traffic control devices, revisions to the application or manner of use of an existing traffic control device, or a provision not specifically described in the MUTCD (e.g., colored temporary pavement markings, alternative signs, and colored drums).

    - ☐ Yes
        - ☐ Describe ____
          ____(or)
        - ☐ Provide Web link ____ (or)
        - ☐ Upload file (*the electronic version of this survey provides options to upload a maximum of two files*)____ (or)
        - ☐ Don’t have information readily available, contact me later
        - ☐ Contact Mr./Ms.:____
          at phone/email: ____
    - ☐ No

36. Are there new or modified traffic control devices would you like to see formally evaluated? List two only and explain why.

    Describe:____
    ____
    ____

4.3 Intermodal Control Strategies

One attribute of constructing projects in urban corridors is that modes such as commercial vehicles and railroads are often present in the same or proximate right-of-way (ROW). The presence of other modes can complicate design, safety, traffic control, productivity, costs, and schedules. If other modes are present in the same corridor, then agencies will most likely have to address these specific issues—from scoping through construction stages.

37. Describe effective TMP strategy(s) your agency has used to mitigate the effects of commercial vehicles and railroad users on significant projects.

    TMP strategy(s) for Commercial Vehicles:____
    ____
    ____

    TMP strategy(s) for Railroad Users (including crossings):
    ____
    ____
    ____

38. Please describe a major road construction project that deployed significant TMP strategies to minimize impacts to commercial vehicle travel (i.e. monitoring/detouring)

    Describe:____
    ____
    ____

39. Please describe a major road construction project that deployed significant strategies to minimize the impact to railroads affected by the construction activities

    Describe:____
    ____
    ____

5 Evaluating Work Zone Strategies

40. Do you have any significant road construction projects awarded in fall/winter 2014 or scheduled to be awarded in 2015? If yes, please list below. These projects may become potential test sites for strategies you suggested for further evaluation. Working with the project staff, the research team will collect and analyze all data.

	Project Name	Contact Info (Email/Phone)
1		
2		

THANK YOU FOR YOUR HELP AND COOPERATION WITH THIS PROJECT!

Appendix A—Survey Form

NCHRP 03-111

Effectiveness of Work Zone Transportation Management Plan (TMP) Strategies

Survey — Part B

Contents

1 Introduction

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Because some questions are open-ended, it may be necessary to conduct follow-up interviews to confirm or enhance the understanding of the responses. For this purpose, please provide your contact information as well as contact information for anyone who has assisted you in completing this survey. We will limit any follow-up calls.

	Contact No. 1	Contact No. 2
Name		
Phone Number		
Email		

This survey can also be completed via a conference call. Please email leverson.boodlal@kls-eng.com, if conference call is your preferred method.

All data obtained from participants will be kept confidential and will only be reported in an aggregate format.

THANK YOU IN ADVANCE FOR YOUR HELP AND COOPERATION WITH THIS PROJECT!

2 Public Information Strategies

Including a public information component in the TMP has the potential to reduce work zone impacts. By providing specific information concerning road projects to road users and the community, you alert them to potential effects and available means to avoid them, as well as more general information concerning appropriate driving and travel behavior and travel options associated with the work zone.

2.1 Public Awareness Strategies

Public awareness strategies include various methods to educate and communicate with the public, businesses, and the community concerning the road project and work zone changes.

1. Public awareness strategies include various methods to educate and communicate with the public, businesses, and the community concerning the road project and work zone changes. Please select from list below and provide as much information as possible.

Public Awareness Strategy List	**Frequency of Use** (1=Selective to a particular project, 2=Frequently, 3=Limited, 4=Don't Know, 5=Not Used)	**Roadways mainly used on** (1=Interstates/Freeways, 2=Arterials, 3=Both)	**Rate Effectiveness** (1=Highly Effective, 2=Moderately Effective, 3=Not Effective, 4=Inconclusive, 5=Don't Know)	**Rate Public Feedback Response (if known)** (1=Very Good, 2=Good, 3=Satisfactory, 4=Poor, 5=Very Poor, 6=Don't Know)
☐Paid advertisements – TV				
☐Paid advertisements – Radio				
☐Social media (Twitter, Facebook, etc.)				
☐Project Web site (general)				
☐Real-time video display of project road/s information on website				
☐Community task forces				

2. Please provide up to two (2) major road construction projects that deployed significant public awareness strategies.

	Project Name	**Public Awareness Strategy Used**
1		
2		

---

3. Do you have any (up to 2) examples of public awareness success stories/lessons learned that would be useful to share with other agencies or explore in greater detail as a case study?

    - ☐ Yes
        - ☐ Describe ____ ____(or)
        - ☐ Provide Web link ____ (or)
        - ☐ Upload file (*the electronic version of this survey provides options to upload a maximum of two files*)____ (or)
        - ☐ Don't have information readily available, contact me later
        - ☐ Contact Mr./Ms.:____ at phone/email: ____
    - ☐ No

4. Has your agency used public information strategies different than the ones listed in Question #1? If so, please describe them.

    Describe:____
    ____
    ____

5. Which public awareness strategies would you like to see formally evaluated? List two only and explain why.

    Describe:____
    ____
    ____

2.2 Motorist Information Strategies

These strategies provide current and/or real-time information to road users regarding the project work zone.

6. Which motorist information strategies has your agency used and what is your experience using them? Please select from list below and provide as much information as possible.

Motorist Information Strategy List	Frequency of Use (1=Selective to a particular project, 2=Frequently, 3=Limited, 4=Don't Know, 5=Not Used)	Roadways mainly used on (1=Interstates/Freeways, 2=Arterials, 3=Both)	Rate Effectiveness (1=Highly Effective, 2=Moderately Effective, 3=Not Effective, 4=Inconclusive, 5=Don't Know)	Rate Public Feedback Response (if known) (1=Very Good, 2=Good, 3=Satisfactory, 4=Poor, 5=Very Poor, 6=Don't Know)
☐Traffic radio				
☐Changeable message signs (CMS)				
☐Temporary motorist information signs				
☐Dynamic speed message sign				
☐Highway advisory radio (HAR)				
☐Highway information network (Web-based)				
☐511 traveler information systems (wireless, handhelds, in-vehicle, etc)				
☐Freight travel information				
☐C-B Wizard Alert System (to transmit project information)				
☐Extinguishable signs				

7. Please provide up to two (2) major road construction projects that deployed significant motorist information strategies.

	Project Name	Motorist Information Strategy Used
1		
2		

____

8. From the strategies selected in Question #6, has your agency conducted any in-house research, before-after studies, field trials, etc. (either published or unpublished such as internal memo)?

   ☐ Yes

      ☐ Describe ____
      ____(or)

      ☐ Provide Web link ____ (or)

      ☐ Upload file (*the electronic version of this survey provides options to upload a maximum of two files*)____ (or)

      ☐ Don't have information readily available, contact me later

      ☐ Contact Mr./Ms.:____
      at phone/email: ____

   ☐ No

9. Has your agency used motorist information strategies different than the ones listed in Question #6? If so, please describe them.

   Describe:____
   ____
   ____

10. Which motorist information strategies would you like to see formally evaluated? List two only and explain why.

   Describe:____
   ____
   ____

THANK YOU FOR YOUR HELP AND COOPERATION WITH THIS PROJECT!

Appendix A—Survey Form

NCHRP 03-111

Effectiveness of Work Zone Transportation Management Plan (TMP) Strategies

Survey — Part C

Contents

1 Introduction

The National Academy of Sciences (NAS), through the Transportation Research Board (TRB), conducts studies relating to contemporary transportation issues. In 1963, the TRB established the National Cooperative Highway Research Program (NCHRP) to administer research projects deemed critical by the American Association of State Highway and Transportation Officials (AASHTO) Standing Committee on Research to the needs of state DOTs.

In 2013, 579 motor vehicle occupants died in highway work zones across the country, with a further 105 worker fatalities. In addition to the safety problem, nearly 24% of non-recurring freeway delay is attributed to work zones, which equates to about 482 million hours and an annual fuel loss of more than $700 million. Many DOTs have implemented TMP strategies—but nationally there is not adequate knowledge of these strategies or their relative effectiveness. This survey is intended to solicit information and perspectives regarding how your agency manages a variety of work zone challenges and how you are finding success in doing so. This survey is divided into three parts: A, B and C.

A. **Part A** relates to 'Transportation Operations (TO)' strategies and 'Temporary Traffic Control (TTC)' strategies. TO and TTC strategies are further sub-divided into various categories:
   i. TO—Demand management strategies
   ii. TO—Corridor/network management (traffic operations) strategies
   iii. TO—Work zone safety management strategies
   iv. TO—Traffic/incident management and enforcement strategies
   v. TTC—Control strategies
   vi. TTC—Traffic control devices
   vii. ICS—Intermodal Control Strategies

B. **Part B** relates to the 'Public Information' strategies, which is sub-divided into 'Public Awareness' and 'Motorist Information' strategies.

C. **Part C** relates to 'Project Coordination & Innovative Construction Strategies'.

The expected outcome of the project will be a Guidebook to help work zone practitioners identify and select the most effective and cost-efficient TMP strategies to implement in a particular construction setting on future projects.

KLS Engineering, LLC is conducting this research under contract to NCHRP. Surveys have been sent to all state DOTs and selected local governments. If you have any questions about this survey or how the data will be used please contact the Principal Investigator, Leverson Boodlal at e-mail leverson.boodlal@kls-eng.com. **A copy of the Guidebook will be mailed to you once the project is completed.**

You are receiving this portion of the survey because you have been identified as the most resourceful person for one of the categories above. Note that other parts of the survey were sent to different departments within your agency for completion.

Because some questions are open-ended, it may be necessary to conduct follow-up interviews to confirm or enhance the understanding of the responses. For this purpose, please provide your contact information as well as contact information for anyone who has assisted you in completing this survey. We will limit any follow-up calls.

	Contact No. 1	Contact No. 2
Name		
Phone Number		
Email		

This survey can also be completed via a conference call. Please email leverson.boodlal@kls-eng.com, if conference call is your preferred method.

All data obtained from participants will be kept confidential and will only be reported in an aggregate format.

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2 Project Coordination & Innovative Construction Strategies

2.1 Project Coordination

Project coordination strategies have the potential to reduce mobility and safety effects of work zone activities.

1. Please describe your agency efforts with utility suppliers to promote proactive coordination of long-range transportation plans with long-range utility plans, with the goal of reducing project delays and minimizing the number of work zones on the highway.

   Describe:____

   ____

   ____

2. Please rate the most effective measures for mitigating the effects of utilities on construction projects.

Utility Coordination Strategy List	**Rate Effectiveness of this strategy** (1=Highly Effective, 2=Moderately Effective, 3=Not Effective, 4=Inconclusive, 5=Don't Know)
☐Early coordination with impacted utility companies	
☐Payment of some relocation expenses, even if not required by law	
☐Litigation	
☐Modifying state law to require more effective coordination between your agency and utility companies	
☐Project specific coordination meetings with utility companies even before construction is started	

3. Please rate the most effective measures for dealing with right-of-way issues relating to construction projects.

Right-of-Way Coordination Strategy List	**Rate Effectiveness of this strategy** (1=Highly Effective, 2=Moderately Effective, 3=Not Effective, 4=Inconclusive, 5=Don't Know)
☐Add additional staff to accelerate the acquisition process	
☐Pay incentives to property owners who agree to sell early in the process	
☐Use private sector resources to fill critical roles and augment agency staff (e.g., appraisers, relocation specialists)	
☐Pay incentives to private sector companies performing acquisition services for your agency	

Right-of-Way Coordination Strategy List	Rate Effectiveness of this strategy (1=Highly Effective, 2=Moderately Effective, 3=Not Effective, 4=Inconclusive, 5=Don't Know)
☐Advertise projects before all parcels have been acquired or right of entry secured	
☐Award projects before all parcels have been acquired or rights of entry secured	
☐Use the construction contractor to acquire rights of entry after awarding the construction contract	
☐Use of the construction contractor to acquire property after awarding the construction contract	

4. Please rate the most effective measures for addressing the efforts of different construction projects within the same limits.

Project Coordination Strategy List	Rate Effectiveness of this strategy (1=Highly Effective, 2=Moderately Effective, 3=Not Effective, 4=Inconclusive, 5=Don't Know)
☐ Coordination during the planning/scoping process	☐ ☐
☐ Coordination during the engineering design process	
☐ Permanent ongoing meetings/committees	
☐ Project specific meetings/committees	
☐ Use in-house staff who are familiar with all projects (no external coordination is necessary)	

5. Please provide a road construction project(s) that involved significant utility project coordination strategies.

Describe:____
____
____

2.2 Contracting and Innovative Construction Strategies

These strategies typically involve contractual agreements to reduce project duration or traffic impact.

6. For ***Design-Build*** projects—please select the reasons for its selection and experiences with reductions in project duration and cost.

Reason (Select Best Two)	Average reductions in project duration[1]	Average reductions in cost[2]
Select two options that apply: ☐ Shorter construction schedule ☐ Price certainty (knowing what the final cost will be) ☐ Opportunities for innovation on the part of designers/contractors ☐ Ease of contract administration on the part of your agency ☐ Improved management of traffic during construction ☐ Improved management of stakeholder issues during construction ☐ Other (describe):______________________________	☐ 0% ☐ 0–10% ☐ 11–20% ☐ >20% ☐ Other, explain ☐ Not Available ☐ Don't Know ☐Other_____________	☐More than 10% under budget ☐0–10% under budget ☐On budget ☐ 0–10% over budget ☐ Other, explain ☐ Not Available ☐ Don't Know

The average reductions in project duration and cost are in comparison to the Design-Bid Build (DBB) method. Please explain if DBB is not used as baseline for comparison.

Describe:____

____

7. For ***Construction Manager At-Risk*** projects—please select the reasons for its selection and experiences with reductions in project duration and cost.

Reason (Select Best Two)	Average reductions in project duration	Average reductions in cost
Select two options that apply: ☐ Shorter construction schedule ☐ Price certainty (knowing what the final cost will be) ☐ Opportunities for innovation on the part of designers/contractors ☐ Ease of contract administration on the part of your agency ☐ Improved management of traffic during construction ☐ Improved management of stakeholder issues during construction ☐ Other (describe):______________________________	☐ 0% ☐ 0–10% ☐ 11–20% ☐ >20% ☐ Other, explain ☐ Not Available ☐ Don't Know ☐Other	☐More than 10% under budget ☐0–10% under budget ☐On budget ☐ 0–10% over budget ☐ Other, explain ☐ Not Available ☐ Don't Know

The average reductions in project duration and cost are in comparison to the Design-Bid Build (DBB) method. Please explain if DBB is not used as baseline for comparison.

Describe:____

____

[1] Relative to estimated or projected cost
[2] Relative to engineer's estimate

8. For ***Public-Private Partnerships***—please select the reasons for its selection and experiences with reductions in project duration and cost.

Reason (Select Best Two)	Average reductions in project duration	Average reductions in cost
Select two options that apply: ☐ Shorter construction schedule ☐ Price certainty (knowing what the final cost will be) ☐ Opportunities for innovation on the part of designers/contractors ☐ Ease of contract administration on the part of your agency ☐ Improved management of traffic during construction ☐ Improved management of stakeholder issues during construction ☐ Other (describe):______________________________	☐ 0% ☐ 0–10% ☐ 11–20% ☐ >20% ☐ Other, explain ☐ Not Available ☐ Don't Know ☐Other	☐More than 10% under budget ☐0–10% under budget ☐On budget ☐ 0–10% over budget ☐ Other, explain ☐ Not Available ☐ Don't Know

The average reductions in project duration and cost are in comparison to the Design-Bid Build (DBB) method. Please explain if DBB is not used as baseline for comparison.

Describe:____

____

9. For ***Indefinite Delivery/Indefinite Quantity (ID/IQ)*** projects—please select the reasons for its selection and experiences with reductions in project duration and cost.

Reason (Select Best Two)	Average reductions in project duration	Average reductions in cost
Select two options that apply: ☐ Shorter construction schedule ☐ Price certainty (knowing what the final cost will be) ☐ Opportunities for innovation on the part of designers/contractors ☐ Ease of contract administration on the part of your agency ☐ Improved management of traffic during construction ☐ Improved management of stakeholder issues during construction ☐ Other (describe):______________________________	☐ 0% ☐ 0–10% ☐ 11–20% ☐ >20% ☐ Other, explain ☐ Not Available ☐ Don't Know ☐Other	☐More than 10% under budget ☐0–10% under budget ☐On budget ☐ 0–10% over budget ☐ Other, explain ☐ Not Available ☐ Don't Know

The average reductions in project duration and cost are in comparison to the Design-Bid Build (DBB) method. Please explain if DBB is not used as baseline for comparison.

Describe:____

____

___

10. For ***Design Sequencing***[3] projects—please select the reasons for its selection and experiences with reductions in project duration and cost.

Reason (Select Best Two)	Average reductions in project duration	Average reductions in cost
Select two options that apply: ☐ Shorter construction schedule ☐ Price certainty (knowing what the final cost will be) ☐ Opportunities for innovation on the part of designers/contractors ☐ Ease of contract administration on the part of your agency ☐ Improved management of traffic during construction ☐ Improved management of stakeholder issues during construction ☐ Other (describe):___	☐ 0% ☐ 0–10% ☐ 11–20% ☐ >20% ☐ Other, explain ☐ Not Available ☐ Don't Know ☐Other	☐More than 10% under budget ☐0–10% under budget ☐On budget ☐ 0–10% over budget ☐ Other, explain ☐ Not Available ☐ Don't Know

The average reductions in project duration and cost are in comparison to the Design-Bid Build (DBB) method. Please explain if DBB is not used as baseline for comparison.

Describe:___

___

11. Please describe any other contracting strategies used.

Description of Other Contracting Strategy:___

What is your experience? (select from below)

Reason (Select Best Two)	Average reductions in project duration	Average reductions in cost
Select two options that apply: ☐ Shorter construction schedule ☐ Price certainty (knowing what the final cost will be) ☐ Opportunities for innovation on the part of designers/contractors ☐ Ease of contract administration on the part of your agency ☐ Improved management of traffic during construction ☐ Improved management of stakeholder issues during construction ☐ Other (describe):___	☐ 0% ☐ 0–10% ☐ 11–20% ☐ >20% ☐ Other, explain ☐ Not Available ☐ Don't Know ☐Other	☐More than 10% under budget ☐0–10% under budget ☐On budget ☐ 0–10% over budget ☐ Other, explain ☐ Not Available ☐ Don't Know

Please explain if DBB is not used as baseline for comparison.

Describe:___

___

[3] Design-sequencing allows the sequencing of design activities to permit each construction phase to commence when design for that particular phase is complete—instead of requiring the design for the entire project to be complete before construction can begin.

____

12. Has your agency used Milestone Payments/Incentives/ Disincentives?

☐ Yes (complete table below)
☐ No (provide reason if possible): ____
____

	Explain
How are costs determined?	____ ____
How is competence measured (duration/days, milestones, level of acceptance, etc.)?	____ ____
Can you provide a project where this strategy was used?	____ ____

13. Has your agency used lane rental?

☐ Yes (complete table below)
☐ No (provide reason if possible): ____
____

	Explain
How are costs determined?	____ ____
How is competence measured (duration/days, milestones, level of acceptance, etc.)?	____ ____
Can you provide a project where this strategy was used?	____ ____

____

14. Has your agency used Active Management Payment Method[4]?

- ☐ Yes (complete table below)
- ☐ No (provide reason if possible): ____

____

	Explain
How are costs determined?	______________________________ ______________________________
How is competence measured (duration/days, milestones, level of acceptance, etc.)?	______________________________ ______________________________
Can you provide a project where this strategy was used?	______________________________ ______________________________

15. Has your agency used No-Excuse Incentive Provision[5]?

- ☐ Yes (complete table below)
- ☐ No (provide reason if possible): ____

____

	Explain
How are costs determined?	______________________________ ______________________________
How is competence measured (duration/days, milestones, level of acceptance, etc.)?	______________________________ ______________________________
Can you provide a project where this strategy was used?	______________________________ ______________________________

[4] This concept provides contractors with an incentive to minimize travel time through the work zone or maximize the availability of open lanes. The agency measures average speed through the work zone and the actual traffic flow. Incentives are based on the measured travel speed and the measured volumes in comparison to theoretical percentages of roadway capacity. Typically to implement such a system, the contractor is required to install traffic monitoring equipment to measure traffic performance through the work zone. Possible performance measurements include travel time through the work zone, queue length, traffic volume, delay time, and crash analyses.

[5] No Excuse Incentive is a method used to motivate the contractor to complete work or open-to-traffic a portion of the work on or ahead of schedule by providing a bonus for early completion or open-to-traffic. A "drop-dead date" is given for completion of a phase or project. If the work is completed in advance of this date, the contractor will receive a bonus. There are no excuses for any reason, such as weather delays or not making the early completion or open-to-traffic date. On the other hand, there are no disincentives or fees (other than normal liquidated damages) for not meeting the early completion or open-to-traffic date.

____

16. Has your agency used Liquidated Savings[6]?

- ☐ Yes (complete table below)
- ☐ No (provide reason if possible): ____
____

	Explain
How are costs determined?	____ ____
How is competence measured (duration/days, milestones, level of acceptance, etc.)?	____ ____
Can you provide a project where this strategy was used?	____ ____

17. Has your agency used Contingency Fund Management[7]?

- ☐ Yes (complete table below)
- ☐ No (provide reason if possible): ____
____

	Explain
How are costs determined?	____ ____
How is competence measured (duration/days, milestones, level of acceptance, etc.)?	____ ____
Can you provide a project where this strategy was used?	____ ____

18. What is your agency's experience (lessons learned) with innovative construction techniques?

Describe:____
____
____

____

[6] Liquidated savings is a process by which the agency pays the contractor a modest incentive for each calendar or working day that the contract is completed ahead of schedule. Liquidated savings tend to be used on projects with limited scope and budget, for which other incentive methods would not be justifiable or affordable. The incentive amount is based on the direct savings to the agency in inspection and contract administration costs.

[7] The purpose of contingency fund management is to identify potential project risks that may cause cost and time growth, estimate these risks, create a contingency fund, and use management strategies to minimize impact to cost and time. Contingency fund management may include periodic risk analysis to refine contract contingencies, continual contingency tracking, a drawdown plan that includes contingency forecasting, and strategies to mitigate risk impacts.

---

19. How has your agency used project phasing/scheduling as a TMP strategy?

    Describe:____

    ____

    ____

20. Can you provide two examples of road construction projects that successfully used different contracting types (DB, CM-At-Risk, P3, IDIQ, DS, etc)?

	Project Name	**Contracting Type Used**
1		
2		

Appendix B—Strategy Cross-reference Matrix

	Strategy	Cost	Cross Reference Type										Potential Benefit				Notes
			High Traffic Volume	Low Traffic Volume	Interstates /Freeways	Multi-lane Divided Facilities	Two-lane, two-way	Urban Areas	Rural Areas	Planning and Design Stage	Contract Stage	In-Construction	M*	S*	CS*	PE*	
Work Zone Safety Management Strategies	Work Zone Posted Speed Limit Reduction	$	X		X	X	X	X		X		X		√			Relationship between speed limits and safety is not well defined. Effect on safety will typically be measurable through safety surrogates.
	Portable Variable Speed Limit System	$$	X		X	X		X		X	X		√	√			Hypothesized to have potential effects on crash reductions, and possibly throughput.
	Temporary Rumble Strips	$	X	X	X	X	X	X	X	X	X	X		√			Encourage safer driving behavior
	Sequential Flashing Warning Lights	$	X		X	X		X		X	X	X		√			Effect on safety will typically be measurable through safety surrogates.
	Automated Flagger Assistance Devices	$$		X			X		X	X	X	X		√		√	Productivity and efficiency effects would occur if the number of flaggers used can be reduced.
	Work Zone Intrusion Alarms	$	X	X	X	X	X	X	X	X	X	X		√			False alarms have limited the effectiveness of this strategy in past assessments. Potential exists to possibly improve worker safety.
	Movable Traffic Barrier Systems	$$$$	X		X	X		X	X		X	X	√	√		√	Effects would be computed relative to a barrier use to no barrier.
Corridor/Network Management Strategies	Lane Merge Systems	$$	X		X	X		X	X	X	X	X	√	√			Mobility and safety effects dependent upon operating condition at lane closure prior to change (extent to which queue jumping occurs).
	Reversible Lanes	$$$	X		X	X		X		X	X		√√				Mobility effects depend on whether positive effects from improving peak direction capacity are offset or exceeded by negative effects of capacity loss in off-peak direction.

	Strategy	Cost	Cross Reference Type										Potential Benefit				Notes
			High Traffic Volume	Low Traffic Volume	Interstates /Freeways	Multi-lane Divided Facilities	Two-lane, two-way	Urban Areas	Rural Areas	Planning and Design Stage	Contract Stage	In-Construction	M*	S*	CS*	PE*	
	Ramp Metering	$$	X		X			X		X	X	X	√√			√	Effects on customer satisfaction could be positive (for main lane drivers) or negative (for entering drivers). Reduction in vehicle demand could yield reduction in crashes, but could also increase those on other routes if diversion occurs.
	Truck Restrictions	$	X		X	X		X	X	X	X	X	√	√			Customer satisfaction effects may be positive or negative depending on user group considered (passenger vehicle drivers versus truck drivers).
Traffic Incident Management and Enforcement Strategies	Queue Warning System (QWS)	$$$	X		X	X		X		X	X	X	√	√√	√		Mobility maintained as safety is improved.
	Work Zone Incident Management Plan	$$	X	X	X	X	X	X	X	X	X		√	√√	√	√	Effects dependent on how much strategy improves response time.
	Temporary Incident Detection and Surveillance System	$$	X		X	X		X	X			X	√	√√	√		Effects dependent on how much strategy improves response time and reduction in secondary crashes.
	Tow/Freeway Service Patrols	$$	X		X	X		X				X	√	√√	√		Possible reduction in secondary crashes
	Traffic Screens (aka Glare Screens aka Gawk Screens)	$	X		X	X		X				X	√	√			Potential to reduce driver distraction.
	Automated Speed Enforcement	$$	X		X	X		X		X				√√			Limited applicability to due legislative changes required.
	Police Enforcement	$$	X		X	X		X		X	X	X		√√			Effects on mobility, customer satisfaction, productivity and efficiency may be positive if presence leads to more consistent speeds and improved driving behavior around work zone, or negative if enforcement efforts are too aggressive.

	Strategy	Cost	Cross Reference Type										Potential Benefit				Notes
			High Traffic Volume	Low Traffic Volume	Interstates /Freeways	Multi-lane Divided Facilities	Two-lane, two-way	Urban Areas	Rural Areas	Planning and Design Stage	Contract Stage	In-Construction	M*	S*	CS*	PE*	
Demand Management Strategies	Strategies to Shift Mode of Travel	$$$$	X		X	X		X		X	X		√	√	√	√	Mobility effects dependent on ability to shift mode choice. Reduction in vehicle demand could yield reduction in crashes. Productivity and efficiency effects would exist if mobility improvements assist materials and equipment delivery.
	Strategies to Shift Time of Travel	$	X		X	X		X		X	X		√√	√	√	√	Mobility effects dependent on ability to shift departure times. Productivity and efficiency effects would exist if mobility improvements assist materials and equipment delivery.
Control Strategies	Full Road Closure	$$		X		X	X	X	X	X						√√	Impacts of full closures on mobility and safety measures throughout corridor may be positive or negative, and would need to be measured against other traffic-handling options available. Strategy would be expected to improve worker safety.
	Night Work	$$	X	X	X	X	X	X	X	X			√√		√	√	Working at night can have negative worker and productivity/efficiency effects if not performed correctly.
	Two-way traffic on one side of divided facility (crossover)	$$	X	X	X	X	X	X	X	X	X			√		√	Effects evaluated relative to part-width construction on each side of facility.
Project Coordination	Project Coordination	$	X	X	X	X	X	X	X	X	X	X	√√	√	√√		Effects depend on how coordination affects duration of conditions impacting mobility and safety.
Innovative Contracting and Construction Strategies	Design-Build Contracting Method	$$$	X	X	X	X		X	X		X					√√	Effects on safety, mobility, and customer satisfaction depend on quality of other TMP strategies implemented.
	Construction Manager / General Contractor (CMGC)	$$	X		X	X		X			X					√	Allow for fast tracking of design and construction activities.
	Cost-Plus-Time (A+B) Selection Method	$$	X		X	X		X			X		√√	√√	√	√√	Allows for innovation, shorter delivery time.
	Incentive / Disincentive Clauses	$$	X		X	X		X			X		√√	√√	√	√√	Minimizes impacts, earlier completion date.
	No Excuse Incentive (NEI)	$$	X		X	X		X			X		√√	√√	√	√√	Minimizes impacts, earlier completion date.

	Strategy	Cost	Cross Reference Type										Potential Benefit				Notes
			High Traffic Volume	Low Traffic Volume	Interstates /Freeways	Multi-lane Divided Facilities	Two-lane, two-way	Urban Areas	Rural Areas	Planning and Design Stage	Contract Stage	In-Construction	M*	S*	CS*	PE*	
	Lane Rental	$$	X		X	X		X			X		√√	√√	√		Effects on productivity and efficiency may be negative if contractor is not able to efficiently fit tasks within allowable work windows.
	Value Engineering		X	X	X	X	X	X	X		X					√	Improve value of project.
Innovative Construction Strategies	Accelerated Construction	$$$$	X		X	X		X			X		√	√	√	√√	Reduce project construction time, cost, and RUC.
Traffic Control Devices	Smart Arrow Boards	$$	X	X	X	X	X	X	X	X	X	X	√	√	√	√√	Potential to provide real time information to public and DOT.
	Lighting Devices	$$	X		X	X	X	X	X	X	X	X	√	√			Effect on safety will typically be measurable through safety surrogates.
Motorist Information Strategies	Speed Feedback Signs	$$	X	X	X	X	X	X	X	X	X	X	√√	√	√√	√	Ability to estimate what would happen if signs are not used. Productivity and efficiency effects would exist if mobility improvements assist materials and equipment delivery.
	Construction Truck Entering and Exit System	$$	X		X	X		X		X	X	X		√			Effect on safety will typically be measurable through safety surrogates.
	Real-time Travel System	$$$	X		X	X		X	X	X	X	X	√√		√	√	Effect on safety and mobility will typically be measurable through related surrogates.
Public Awareness Strategies	Program-level Public Information and Outreach Campaigns	$$	X	X	X	X	X	X	X	X		X	√	√	√		Effect on safety will typically be measurable through surrogates.
	Project-Level Public Information Strategies	$$	X	X	X	X	X	X	X	X		X	√	√	√√		Effect on safety will typically be measurable through surrogates.

* M: Mobility; S: Safety; CS: Customer Satisfaction; PE: Agency/Contractor Productivity and Efficiency   Cost: Low ($) to High ($$$$)