

# Multi-Modal Intelligent Traffic Signal Systems (MMITSS) Impacts Assessment

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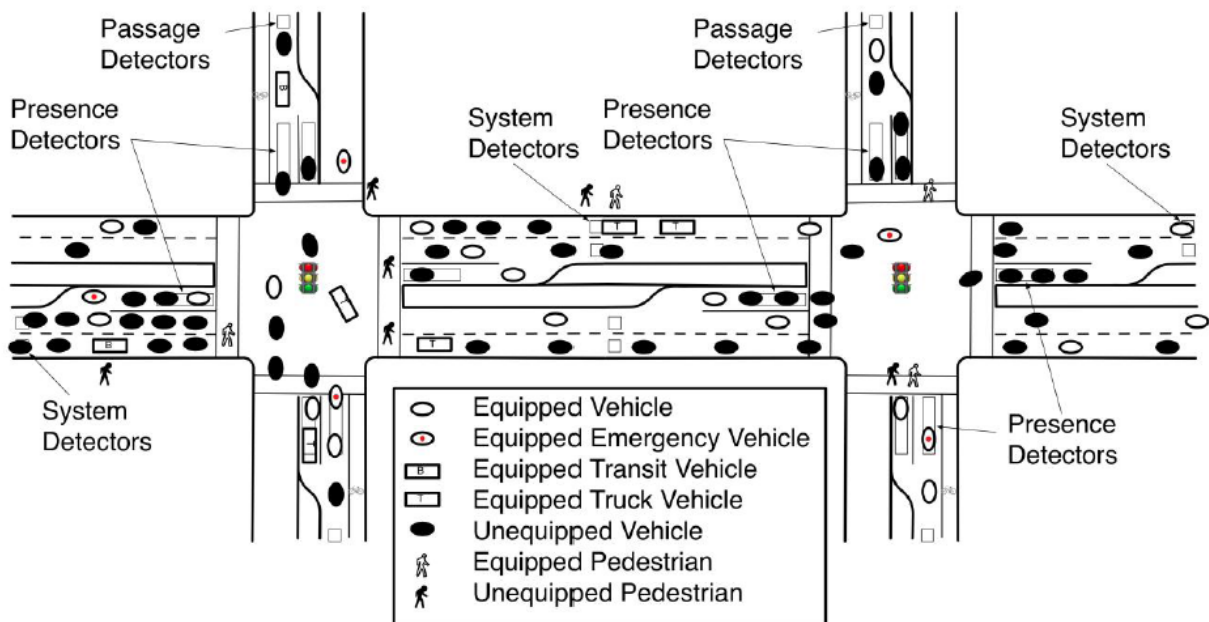


# Executive Summary

This document is the Task 12 deliverable, the final report on Impacts Assessment, for the task order Impacts Assessment of Multi-Modal Intelligent Traffic Signal Systems (MMITSS) (Contract: DTFH61-12-D-00020). The purpose of this task order has been to:

- (i) Assess the impacts of prototypes of Intelligent Traffic Signal System (I-SIG), Transit Signal Priority (TSP), Freight Signal Priority (FSP), and the combination of TSP and FSP applications. (The prototypes were developed by the Prototype Development (PD) team.)
- (ii) Assess the impacts of the prototypes at various levels of potential future market penetration.

MMITSS is a next-generation traffic signal system that seeks to provide a comprehensive traffic information framework to service all modes of transportation. Figure ES-1 below illustrates an example of the MMITSS applications.



**Figure ES-1. Illustration of the MMITSS Concept**

Source: "MMITSS Final ConOps," University of Arizona et al. [1]

MMITSS is composed of several component applications, including:

- I-SIG, an overarching system optimization application accommodating signal priority, preemption, and pedestrian movements;
- TSP and FSP, which provide signal priority to transit vehicles at intersections and along arterial corridors or to freight vehicles along an arterial corridor near a freight facility, respectively;
- PED-SIG, an application that allows for an automated call from the smart phone of a visually impaired pedestrian to the traffic signal, as well as audio cues to safely navigate the crosswalk; and
- Emergency Vehicle Preemption (PREEMPT), which provides signal preemption to emergency vehicles and accommodates multiple emergency requests.

The study investigated the impacts of four operational scenarios, namely: I-SIG, TSP, FSP, and the combination of TSP and FSP applications. An impacts assessment (IA) plan was prepared to ensure that the assessment addressed the following topics identified in the project management plan:

- Lessons learned and observations from the prototype IA process.
- Suggestion of recommended changes to performance measures or targets.
- Estimation of impacts of a mature deployment of the applications based on site-independent findings of the prototype.
- Sensitivity of performance estimates to key inputs that may be subject to a high level of uncertainty spanning both stated assumptions and utilized data.

## Measures of Effectiveness

For the prototype field data tests, the research team selected the following top-priority performance measures for determining effectiveness of the signal system:

- Travel times
- Delay times
- Vehicle stops

For the simulation tests, the following top-priority performance measures were selected for determining system effectiveness:

- Travel times
- Delay times

## Objectives

The IA was planned such that the following key questions could be addressed:

- Are individual MMITSS applications more beneficial when implemented in conjunction or in isolation? Under what operational conditions are particular applications the most beneficial? Under what conditions is one application superior to the other? Under what conditions is the combined MMITSS applications expected to be most beneficial? (NOTE: Operational conditions describe the frequency and intensity of specific traffic conditions experienced in the prototype deployment sites over the course of a year. Operational conditions are identified by a combination of specific traffic demand levels (e.g., low, medium, or high demand).
- What are the potential impacts of MMITSS deployments over time? At what levels of market penetration of connected vehicle technology do individual MMITSS applications and the MMITSS bundle as a whole become effective?

To answer these key questions, the MMITSS IA plan included two major tasks: (1) field data analyses utilizing the data collected from one MMITSS prototype and (2) simulation analyses to assess the performance of MMITSS applications at the prototype site and a second site. Evaluation of the second site was intended to facilitate a site-independent analysis of MMITSS impacts and to identify possible impacts on regions that deploy single or multiple MMITSS applications.

The MMITSS system is intended to improve and/or redistribute system mobility across multiple modes of travel at signalized intersections. The overall objective of MMITSS is to assess the potential impacts and benefits of the MMITSS technology and the potential deployment of the combination of MMITSS applications. Further, the simulation study identifies the most beneficial operational conditions for each MMITSS scenario.

## Approach

The technical approach for the IA was organized into five phases:

1. Determination of Operational Scenario Data Needs and Assumptions
2. Data Collection
3. Development of Test Network
4. Data Analysis
5. Development of IA Document

## Findings

The primary findings of the research study are as follows:

- The field data collection found that the MMITSS I-SIG, FSP, and the combination of TSP and FSP applications effectively improved vehicle travel time and travel time reliability, and reduced the delay for equipped passenger car, trucks, and transit vehicles on the test facility.

- In particular, FSP effectively reduced the delay of connected trucks and unequipped vehicles by up to 20.9 percent and 26.0 percent, respectively, compared with the base case operations. Field-collected data found that the combination of TSP and FSP operations improved connected bus travel times by 8.2 percent and connected truck travel times by 39.7 percent. I-SIG marginally improved travel times for both equipped and unequipped vehicles compared with the base case scenarios. However, the study found that I-SIG considerably improved travel time reliability by up to 56 percent compared with the base case.
- The Arizona simulation study found that I-SIG achieved vehicle delay reductions of 20 percent and TSP effectively saved travel time for both transit and passenger vehicles on the corridor where TSP was operated but occasionally increased the system-wide delay due to reduced green times on the side streets. FSP simulation results indicated that FSP successfully reduced travel times by up to 20 percent for connected trucks. However, the FSP application also increased system-wide delay due to increased delays on side streets. The simulation study found that the combination of TSP and FSP applications was effective in assigning priority to trucks based on a predefined hierarchy of control.
  - The Virginia simulation study demonstrated that I-SIG reduced vehicle delay by up to 35 percent and increased average traffic stream speed by up to 27 percent. In addition, TSP reduced travel time for both transit and passenger vehicles on the corridor by up to 29 percent and 28 percent, respectively. However, TSP can increase system-wide delay because it reduces green times on the side streets. The study also demonstrated that FSP can be effectively utilized along major freight routes. While FSP significantly reduces truck delay, network-wide delay is increased substantially, especially in the high truck composition scenario. The simulation study found that the combination of TSP and FSP applications successfully executed a hierarchical level of priority providing higher priority for trucks in the Virginia test network.
  - The study concludes that the MMITSS I-SIG, TSP, FSP, and the combination of TSP and FSP applications improve vehicle travel time, delay, and travel time reliability for equipped and potentially non-equipped vehicles depending on the scenarios considered, but the tradeoff is that it may produce overall system-wide negative impacts. MMITSS, in its current form, appears to be effective in allowing system managers to allocate and prioritize system capacity/mobility but may not always reduce delay or aggregate system performance.

# Chapter 1 Introduction

## 1.1 Project Background

### 1.1.1 Objectives

The objective of this project is to assess the potential impacts and benefits of the Multi-Modal Intelligent Transportation Signal Systems (MMITSS) technology, and the potential deployment of MMITSS applications. These applications include Intelligent Traffic Signal System (I-SIG), Transit Signal Priority (TSP), Mobile Accessible Pedestrian Signal System (PED-SIG), Freight Signal Priority (FSP), and Emergency Vehicle Preemption (PREEMPT). MMITSS is one of six bundles that have been prioritized by the U.S. Department of Transportation (U.S. DOT) for further development and investigation to expedite efficient deployment of technologies and applications to improve the safety, mobility, and environmental impact of the transportation system. Fully integrated, the MMITSS bundle seeks to improve mobility through signalized corridors using advanced communications and data to facilitate the efficient travel of passenger vehicles, pedestrians, transit, freight, and emergency vehicles through the system. This capability is based on a conceptual understanding of the individual applications, but has not yet been assessed to quantify the potential performance improvements. Moving beyond conceptual formulations of the applications, the next challenge for the MMITSS bundle and larger Dynamic Mobility Applications (DMA) program is to determine the feasibility of application deployment, to determine the impacts of each application, and to identify any compound benefits from coordinated deployment of multiple applications (U.S. Department of Transportation 2015).

### 1.1.2 Scope

The project was designed to ensure that outcomes of the MMITSS Impacts Assessment (IA) align with the needs of the MMITSS Prototype Development (PD), Analysis, Modeling, and Simulation (AMS) Testbed and National-Level DMA Program Evaluation Contractors. This required close coordination with the PD contractor and comprehensive consideration of the data and modeling needs specific to the MMITSS applications. The IA plan was incrementally updated throughout the duration of the project.

The University of Arizona in partnership with the University of California, Berkeley, Savari, Econolite, and SCSC collaborated in the MMITSS Prototype Development, which included the MMITSS system, software development, and real-time field implementation for testing and data collection. The PD team was responsible for the development of the prototype and for testing to verify that the prototype was functioning correctly. The IA team was responsible for integrating the field-collected data and resulting output from the prototype field test into a broader and independent assessment of the impacts of the prototype field test. Further, the study focused on the evaluation of the MMITSS system using simulation analyses to assess the performance of MMITSS applications at the prototype sites and an

independent site. The simulation study of the independent site assessed broader independent impacts of the MMITSS system on this proposed facility using the results and lessons learned from the prototyping effort.

## 1.2 Document Layout

This report is organized into six chapters. The second chapter provides an overview of MMITSS prototype development. The section discusses the role of the PD team, the MMITSS prototypes, and the tasks that were performed by the PD team. The third chapter presents an overview of the assessment methodology, including the operational scenarios, field data collection, and the simulation modeling setup and analyses. Quantitative data analysis was driven by measures of effectiveness (MOEs) selected by the research team. This IA report also includes a qualitative analysis of data to identify potential impacts of deploying multiple MMITSS applications in parallel, as well as site-independent assessment of the bundle. Chapter 4, MMITSS Impacts Assessment, analyzes the field data utilizing the data collected from the Arizona MMITSS prototype and evaluates the performance of MMITSS applications at the Arizona prototype site and at an additional independent site using simulation analyses. Chapter 5 identifies gaps and sets priorities for future research in the area of MMITSS and related connected vehicle (CV) research. The chapter considers design issues in the development of MMITSS simulation model and valid and reliable measures of MMITSS applications that might be helpful in the future study and promotion of MMITSS research. Finally, chapter 6 provides a summary of the findings and the conclusions of the research effort.

# Chapter 2 Prototype Development Description

## 2.1 Prototype Deployment Overview

The MMITSS prototype development is part of the Cooperative Transportation System Pooled Fund Study (CTS PFS) entitled “Program to Support the Development and Deployment of Cooperative Transportation System Applications.” The CTS PFS was created by a group of state and local transportation agencies and the Federal Highway Administration (FHWA), with the Virginia Department of Transportation (VDOT) serving as the lead agency. The focus of the project is on prototyping and testing practical infrastructure-oriented applications that lead to deployment rather than developing theoretical applications. MMITSS is one of the DMAs that have been prioritized by the U.S. Department of Transportation (U.S. DOT) to make surface transportation safer, smarter, and greener by using wireless technology capabilities. DMAs include the Enable Advanced Traveler Information System (EnableATIS), the Freight Advanced Traveler Information System (FRATIS), the Integrated Dynamic Transit Operation (IDTO), Intelligent Network Flow Optimization (INFLO), MMITSS, and the Response, Emergency Staging and Communications, Uniform Management, and Evacuation (R.E.S.C.U.M.E.) system.

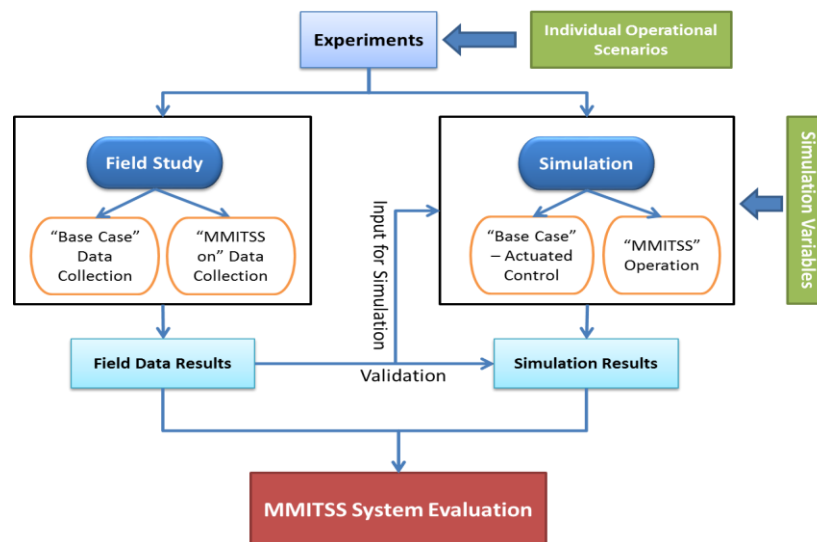
## 2.2 MMITSS Prototype Development

The University of Arizona in partnership with the University of California, Berkeley, Savari, Econolite, and SCSC initiated the MMITSS PD, which included the development of the Concept of Operations (ConOps), determination of the MMITSS system requirements, and the high-level MMITSS system design. The tasks of MMITSS PD team were then extended to include detailed design, system development, system integration and laboratory testing, field integration, testing, evaluation, and finally a demonstration of the system at test beds in Arizona and California. Each field site is based on different technology, which will allow the high-level design to distinguish between common and custom design features required for the MMITSS implementation. Common operational scenarios are planned for both test beds. When the California test bed becomes operational, a comparison of the test results of two the MMITSS prototypes will demonstrate the ability to provide the same functionality on different implementations and networks of the MMITSS applications.

# Chapter 3 Assessment Methodology

## 3.1 Technical Approach

The MMITSS IA included two major tasks: (1) field data analyses utilizing the data collected from two MMITSS prototypes and (2) simulation analyses to assess the performance of various MMITSS applications. Figure 3-1 illustrates the experimental design approach used to fully investigate MMITSS system performance. “Base case” (or “MMITSS off”) and “MMITSS on” field data studies were conducted to assess the performance of individual MMITSS applications under real-world conditions. The simulation study evaluated and demonstrated the impacts of deploying MMITSS applications and strategies in a simulation environment with various operational conditions. The ground findings from the field data study were utilized to expand the evaluation of the broader impacts of MMITSS. The simulation environment was customized to match the traffic signal controller interface, communications environment, and priority algorithms. Major simulation variables included Throughput Volumes, Market Penetration of Connected Vehicles, and Traffic Composition. Then, the simulation study identified the most beneficial operation conditions for each scenario that could be identified by a combination of specific traffic demand levels.



**Figure 3-1. Experimental Design for the IA**

The IA plan made the following assumptions:

- Basic components of the connected vehicle system (roadside equipment [RSE] and onboard equipment [OBE]) are configured properly, powered-on, and communicating with the infrastructure.



- The priority server can accurately predict arrival times of requesting vehicles to the intersection, and must process multiple signal priority requests simultaneously.
- The MMITSS system has an intelligent algorithm for providing priority signalization, based on a predefined hierarchy of control.
- Each signalized intersection on the study corridors is equipped with an RSE.

## 3.2 Operational Scenarios

The overall objective of the MMITSS system is to improve system mobility across multiple modes at signalized intersections. In particular, the study assesses overall system-wide delay and throughput considering various forms of control and signal priority implemented in an isolated intersection or in network environment. In order to implement the MMITSS application, the following operational scenarios were initially selected by the PD team and approved by the U.S. DOT (University of Arizona et al 2012):

1. I-SIG: Basic Signal Actuation
2. I-SIG: Coordinated Section of Signals
3. I-SIG: Dilemma Zone Protection
4. TSP: Basic Transit Signal Priority
5. TSP: Extended Transit Signal Priority
6. PED-SIG: Equipped, Non-Motorized Traveler
7. FSP: Basic Freight Signal Priority Scenario
8. FSP: Coordinated Freight Signal Priority along a Truck Arterial
9. PREEMPT: Single Intersection Emergency Vehicle Priority/Preemptions
10. The Combination of TSP and FSP applications

Some applications within the MMITSS operational scenarios were not ready for testing within the time period of this project. These included coordinated signal operations, PED-SIG, Emergency Vehicle Preemption (PREEMPT), and any combination applications that would have required these component applications.

Thus, this study focuses on the evaluation of the I-SIG, TSP, FSP, and the combination of TSP and FSP applications. The combination of TSP and FSP applications evaluates the applicability of the combined MMITSS applications. The scenario provides a hierarchical level of priority, which can facilitate regional policies and preferences for priority control.

## 3.3 Performance Measures

Quantitative data analysis was driven by the MOEs that were selected by the research team. This IA report also includes a qualitative analysis of the data to identify potential impacts of deploying multiple MMITSS applications, as well as site-independent assessment of the applications.

Scenario performance was assessed by link travel time, delay, average speed, and vehicle stops. Vehicle stops were then used to estimate a proportion of vehicles arriving while the signal is green.

Typically, these measures must be obtained through monitoring of high-resolution occupancies, requiring advance detectors or floating car data.

Table 3-1 provides a summary of the MOEs for each operational scenario that was originally proposed by the research team. Top-priority performance measures that were selected for determining system effectiveness are marked with an “O” Additional performance measures that were considered by the research team but not selected due to the limitation of implementation are marked with an “x.”

**Table 3-1. Data Needs for MMITSS Impacts Assessment by Operational Scenario**

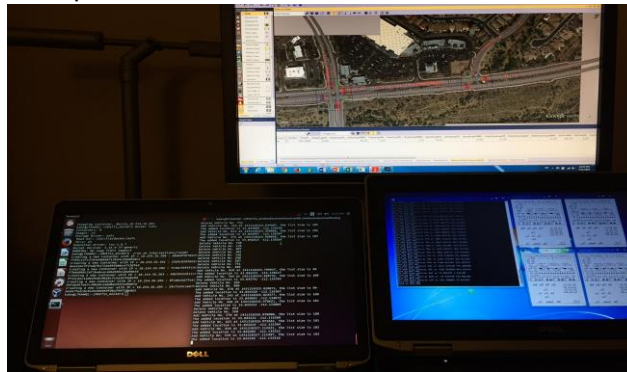
| MOE   | Operational Scenario                     |                     |                         |           |              |                        |                   |                         |             |                        |
|---|--|---------------------|-------------------------|-----------|--------------|------------------------|-------------------|-------------------------|-------------|------------------------|
|   | Basic Signal Actuation                   | Coordinated Signals | Dilemma Zone Protection | Basic TSP | Extended TSP | Non-Motorized Traveler | Basic Freight TSP | Coordinated Freight TSP | EV Priority | Combination of TSP/FSP |
|   | Travel Time                              | x                   |                         | O         | x            | x                      | O                 | x                       | x           | O                      |
|   | Delay                                    | O                   | x                       |           | O            | x                      | x                 | O                       | x           | O                      |
|   | Average Speed                            | O                   | x                       |           | O            | x                      | x                 | O                       | x           | O                      |
|   | Number of Vehicle Stops                  | O                   | x                       |           | O            | x                      | x                 | O                       | x           | O                      |
|   | System-wide Delay, Speed, Vehicle Stops  |                     | x                       | x         |              | x                      | x                 | O                       | x           | O                      |
|   | Occurrence of Dilemma Zone Decisions     |                     |                         | x         |              |                        |                   |                         |             |                        |
|   | Transit Travel Time and Delay            |                     |                         |           | O            | x                      |                   |                         |             | O                      |
|   | Average Person Delay                     |                     |                         |           | x            | x                      |                   |                         |             | x                      |
|   | Truck Travel Time and Delay              |                     |                         |           |              |                        |                   | O                       | x           | O                      |
|   | Fuel Consumption and Emissions by Trucks |                     |                         |           |              |                        |                   | x                       | x           |                        |
| Accuracy of Multiple Priority Request Process |  |                     |                         |           |              |                        |                   |                         | O           |                        |

In the field study, MOEs were obtained from vehicle trajectory data using a Global Positioning System (GPS). The team assessed impacts in comparison to “base case data” from field testing. For each operational scenario, the team collected “base case” (or “MMITSS off”) data. Further, the “after” (or “MMITSS on”) data were collected under similar operational conditions. Both the absolute difference and relative difference between the proposed scenario and the “base case” will be presented later.

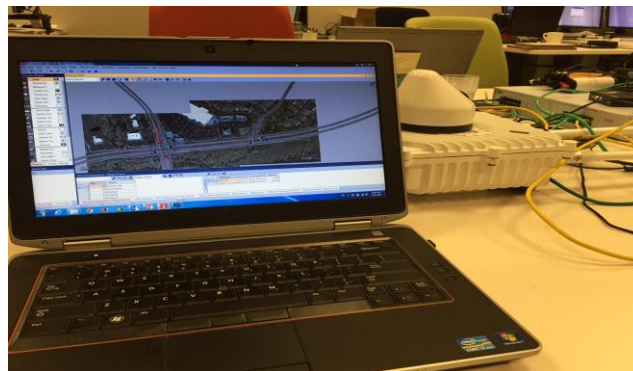
### 3.4 Simulation Modeling Approach

The proposed study evaluates the impacts of MMITSS using a software-in-the-loop simulation (SILS) system that was developed by The University of Arizona PD Team. The PD team also developed a hardware-in-the loop simulation (HILS) system but it was not utilized for the project. Both the HILS and the SILS system are illustrated in Figure 3-2.

The MMITSS simulation platform consists of the VISSIM microscopic traffic simulation software, the basic safety message (BSM) distributor (or Signal Request Messages [SRM] distributor) program, an RSE module, and the Econolite ASC/3 traffic controller emulator. VISSIM, the BSM distributor, and the Econolite ASC/3 traffic controller emulator run on a Windows platform, whereas the RSE module runs on a Linux platform. The two platforms were connected via an Ethernet cable.



(a) SILS System



(b) HILS System

**Figure 3-2. SILS and HILS Setups**

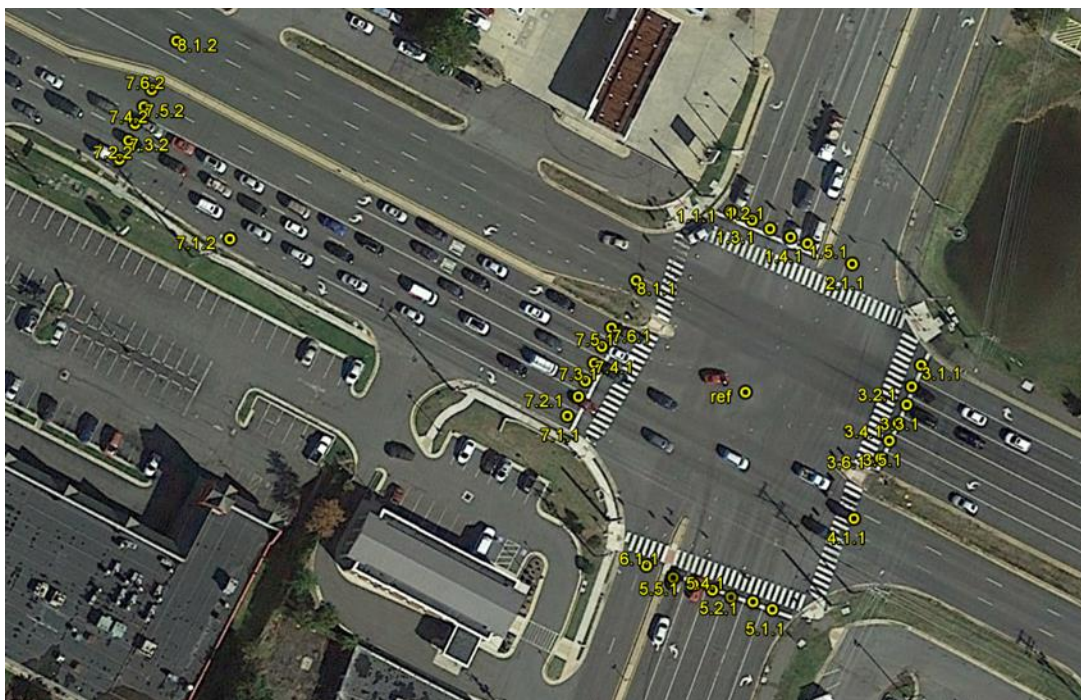
Figure 3-3 illustrates a screenshot of VISSIM simulation model. The location information of network objects in the simulation model should be exactly identical to the real network. In particular, MMITSS modeling requires that the link information, including location, width, and length, is matched to the real roadway to identify vehicle location information in the simulation model, as shown in the figure. The MMITSS modeling requires a precise match between a reference point in VISSIM's x-y coordinate system and the GPS latitude and longitude values from a map file to identify vehicle locations in VISSIM.

The program utilizes high-resolution map information to identify the location of vehicles, as illustrated in Figure 3-4. Each intersection requires a single map file that includes the latitude and longitude coordinates of each lane of roadway within the communication ranges of each RSE. A straight section of a link requires less map points than a curved section. For example, the sample map file in the figure includes 75 map points at a single intersection. A map file includes the following information: Intersection ID, Attributes, Reference Point, Approach, Lane, Lane Attributes, Lane Width, Lane Nodes, Lane Connections, and Reference Lane. The reference point in the middle of an intersection is the location of the RSE in the simulation model whereas in actual practice an RSE is typically installed on one of the traffic signal heads.



**Figure 3-3. VISSIM Virginia Simulation Model Image (Source: Map data ©2015 Google, Imagery ©2015)**





**Figure 3-4. Sample Virginia Map File (Source: Map data ©2015 Google, Imagery ©2015)**

The information flow diagram of the MMITSS simulation platform is illustrated in Figure 3-5. Vehicle mobility data that include individual CV location and speed data are generated from VISSIM, and CV data are transmitted to the BSM distributor program. The CV is modeled as a separate vehicle class using a Dynamic Linked Library (DLL) that is utilized in VISSIM. In Figure 3-3, the red-colored vehicles represent the CVs while the blue-colored vehicles are regular vehicles. The BSM distributor sends BSM data to an RSE when vehicles enter a preset Dedicated Short Range Communications (DSRC) communication range for each traffic signal controller. Figure 3-6 provides a screenshot of the BSM distributor. The figure shows the vehicle's BSM data that are transmitted to an RSE when the vehicle enters RSE communication range with a unique vehicle ID and the vehicle location data in VISSIM's x-y coordinate format. Then, the vehicle location data are converted to latitude and longitude values to identify the precise location of each vehicle using the map file information.

The RSE module utilizes a Containerization Technology provided by a Docker software. Each Docker container runs an individual RSE module, and multiple Docker containers can be run on a single Linux computer. For this study, six containers were run at the same time to operate six signalized intersections. The optimum signal timing data that includes an optimal signal sequence and duration for each phase are estimated by the phase allocation algorithm (Yiheng Feng 2015). The optimal solution is transmitted to the Econolite ASC/3 traffic controller interface. VISSIM updates the signal times through National Transportation Communications for ITS Protocol (NTCIP) commands.

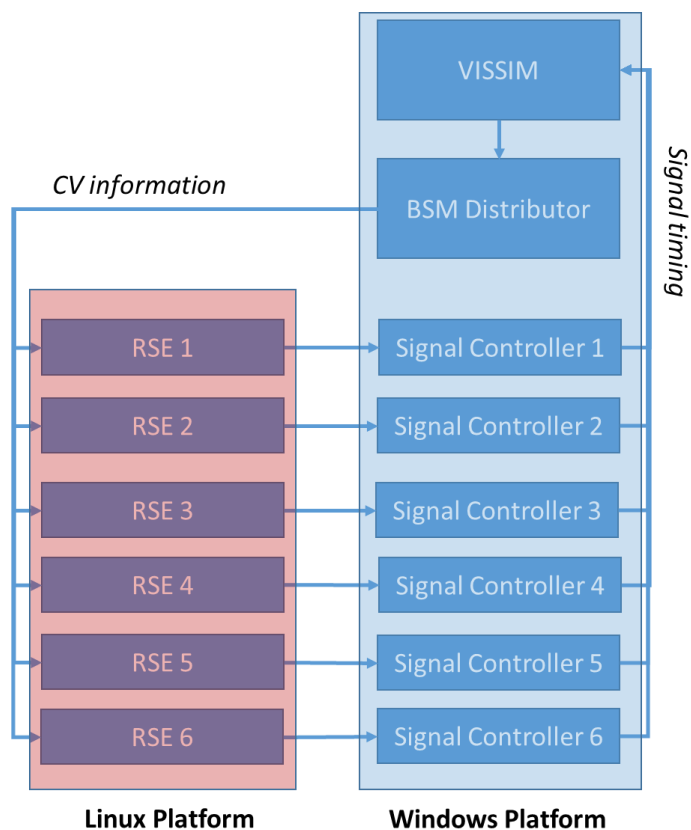


Figure 3-5. SILS Diagram

```

C:\Users\kahn\Desktop\MMITSS_VISSIM\VA_rt50_vissim\BSM_Distributor_new\Debug\BSM_Distrib...
Send to RSE 503
Get BSM from vehicle 491 at 543.614392 -51.840085
Send to RSE 502
Get BSM from vehicle 493 at 551.031893 -41.103668
Send to RSE 502
Get BSM from vehicle 400 at 1729.067526 -845.660064
Send to RSE 505
Get BSM from vehicle 410 at 1784.165114 -872.970516
Send to RSE 505
Get BSM from vehicle 424 at 1891.464712 -933.841534
Get BSM from vehicle 72 at -15.894987 -42.443999
Send to RSE 501
Get BSM from vehicle 318 at 345.741977 -240.911882
Send to RSE 502
Get BSM from vehicle 229 at 2068.769584 -1041.222694
Send to RSE 506
Get BSM from vehicle 382 at 2019.866196 -1016.699320
Send to RSE 506
Get BSM from vehicle 250 at 1937.256177 -975.286316
Send to RSE 506
Get BSM from vehicle 268 at 1912.948046 -963.101940
Send to RSE 506
Get BSM from vehicle 488 at 2256.534301 -930.615073
Send to RSE 506
Get BSM from vehicle 49 at -3.618017 -40.767570
Send to RSE 501
Get BSM from vehicle 395 at 1707.250205 -832.286568
Send to RSE 505
Get BSM from vehicle 222 at 13.153153 31.097498
Send to RSE 501
Get BSM from vehicle 277 at 15.434987 37.214859
Send to RSE 501
Get BSM from vehicle 87 at 12.120671 38.369490
Send to RSE 501
Get BSM from vehicle 303 at 899.386813 -435.568932
  
```

Figure 3-6. BSM Distributor

Table 3-2 through Table 3-5 illustrate simulation scenarios for the I-SIG, TSP, FSP, and the combination of TSP and FSP applications. Volume capacity ratio (V/C) is a commonly-used index for conveying congestion levels. Three congestion levels were investigated within the simulation model with V/C ratios of 0.5, 0.85, and 1.0, representing under-capacity, near-congested and congested conditions, respectively (Rodegerdts, Nevers et al. 2004).

**Table 3-2. I-SIG Simulation Scenarios**

| Traffic Volume                     | Control Group                           | Experimental Group |                  |                  |
|------------------------------------|---|--------------------|------------------|------------------|
|                                    | Base Case (MMITSS-off Actuated Control) | I-Sig I            | I-Sig II         | I-Sig III        |
| Under Capacity (V/C ratio 0.5)     | 100% NEV                                | 25% CV & 75% NEV   | 50% CV & 50% NEV | 75% CV & 25% NEV |
| Near Capacity (V/C ratio 0.85)     | 100% NEV                                | 25% CV & 75% NEV   | 50% CV & 50% NEV | 75% CV & 25% NEV |
| Unstable Condition (V/C ratio 1.0) | 100% NEV                                | 25% CV & 75% NEV   | 50% CV & 50% NEV | 75% CV & 25% NEV |

Note – NEV: Non-equipped vehicle, CV: Connected passenger vehicle

**Table 3-3. TSP Simulation Scenarios**

| Traffic Volume                     | Control Group                           | Experimental Group |
|------------------------------------|---|--------------------|
|                                    | Base Case (MMITSS-off Actuated Control) | TSP                |
| Under Capacity (V/C ratio 0.5)     | 2% NET and 98% NEV                      | 2% CT and 98% NEV  |
| Near Capacity (V/C ratio 0.85)     | 2% NET and 98% NEV                      | 2% CT and 98% NEV  |
| Unstable Condition (V/C ratio 1.0) | 2% NET and 98% NEV                      | 2% CT and 98% NEV  |

Note – NET: Non-equipped transit, CT: Connected transit

**Table 3-4. FSP Simulation Scenarios**

| Traffic Volume                 | Control Group                             |  | Experimental Group |                    |
|--------------------------------|---|--|--------------------|--------------------|
|                                | Base Case I (MMITSS-off Actuated Control) | Base Case II (MMITSS-off Actuated Control) | FSP I              | FSP II             |
| Under Capacity (V/C ratio 0.5) | 20% NEF and 80% NEV                       | 80% NEF and 20% NEV                        | 20% CF and 80% NEV | 80% CF and 20% NEV |
| Near Capacity (V/C ratio 0.85) | 20% NEF and 80% NEV                       | 80% NEF and 20% NEV                        | 20% CF and 80% NEV | 80% CF and 20% NEV |

Note – NEF: Non-equipped freight, CF: Connected freight

**Table 3-5. The Combination of TSP and FSP Simulation Scenarios**

| Traffic Volume                     | Control Group                           | Experimental Group                  |
|------------------------------------|---|-------------------------------------|
|                                    | Base Case (MMITSS-off Actuated Control) | Combination of TSP/FSP Applications |
| Under Capacity (V/C ratio 0.5)     | 2% NET, 20% NEF, and 78% NEV            | 2% CT, 20% CF, and 78% NEV          |
| Near Capacity (V/C ratio 0.85)     | 2% NET, 20% NEF, and 78% NEV            | 2% CT, 20% CF, and 78% NEV          |
| Unstable Condition (V/C ratio 1.0) | 2% NET, 20% NEF, and 78% NEV            | 2% CT, 20% CF, and 78% NEV          |



# Chapter 4 MMITSS Impacts Assessment

The MMITSS IA included two major tasks: (1) field data analyses utilizing the data collected from the Arizona MMITSS prototype and (2) simulation analyses to assess the performance of MMITSS applications at the Arizona prototype sites and an additional independent site. The evaluation of the additional site facilitated a site-independent analysis of the MMITSS impacts, which will help to identify any anticipated impacts on regions that deploy single or multiple MMITSS applications. Selection of the additional site was discussed with the U.S. DOT Project Review Team and the Route 50-Chantilly, Virginia, site was finally selected.

## 4.1 Arizona Field Data Collection

The objective of field data collection was to evaluate the Arizona MMITSS applications. The study quantified the effectiveness of Arizona MMITSS applications and investigated the performance of side streets using field data. The following three operational scenarios were selected:

1. I-SIG: Basic Signal Actuation
2. FSP: Basic Freight Signal Priority Scenario
3. The combination of TSP and FSP applications

The I-SIG scenario investigates the effectiveness of optimum traffic signal control system for OBE-equipped vehicles to reduce vehicle stops and maximize throughput volume. When OBE-equipped vehicles reach the DSRC communications range, the RSE begins to receive BSMs from the vehicle. Using the vehicle information from the RSE processor, the system calculates estimated vehicle arrival time. Then, using the strategic priority algorithm and vehicle arrival time, the system finds the desired service phase with a phase allocation algorithm. Finally, the optimum phase sequence and timing is processed to the signal controller.

In the FSP case, when an equipped truck reaches the communications range, the RSE receives a Signal Request Message (SRM) from the truck. The MMITSS system continuously tracks the movement of the truck, estimates its arrival time at the stop bar, and matches the estimated arrival time with Signal Phase and Timing (SPaT) to determine the signal phase when the truck is going to arrive at the intersection. The MMITSS system determines the best priority timing based on the prevailing traffic conditions and the level of priority requested by the truck. The RSE either holds the green for the truck's direction of travel if the level of requested priority indicates the truck cannot make a safe stop, or decides if the phase should terminate based on prevailing traffic conditions. When the truck clears the intersection, the OBE sends a cancel SRM to the RSE. The RSE receives the cancel SRM and manages the traffic signal controller to end the priority granting and returns to the normal traffic signal control.

The combination of TSP and FSP applications investigates how equipped transit and freight vehicles operate in a single intersection and how priority is given to multiple equipped vehicles. Equipped vehicles, including transit and freight vehicles, can actively participate in requesting SRMs. The MMITSS system can process multiple requests for priority that may be received from multiple

vehicles, as well as multiple modes, at any time. To manage these multiple requests, the MMITSS system provides a hierarchical level of priority that can facilitate preferences for priority control. During the field data collection, the same level of priority was given to both equipped transit and freight vehicles.

### 4.1.1 Site Description

To investigate the impacts of MMITSS applications, natural driving data and queue data were collected at the Arizona Connected Vehicle Test Bed in Anthem, Arizona. The test bed consists of six intersections along a major arterial road, Daisy Mountain Drive.

The test bed starts at Gavilan Peak Parkway to the west and extends to Anthem Way to the east. The section extends 1.9 miles (3.04 km) and covers six signalized intersections.

The study corridor is a divided six-lane neighborhood road (three lanes for direction) with a speed limit of 40 mi/hr (or 64 km/h). The study section is closely located (within 0.5 miles) and connected to an interstate highway (I-17), which is a major link that connects to the Phoenix metropolitan area. Thus, the study corridor is frequently used as a commuter route to Phoenix, Arizona, and traffic flows along the corridor are typically directional. Figure 4-1 illustrates the Arizona test bed.

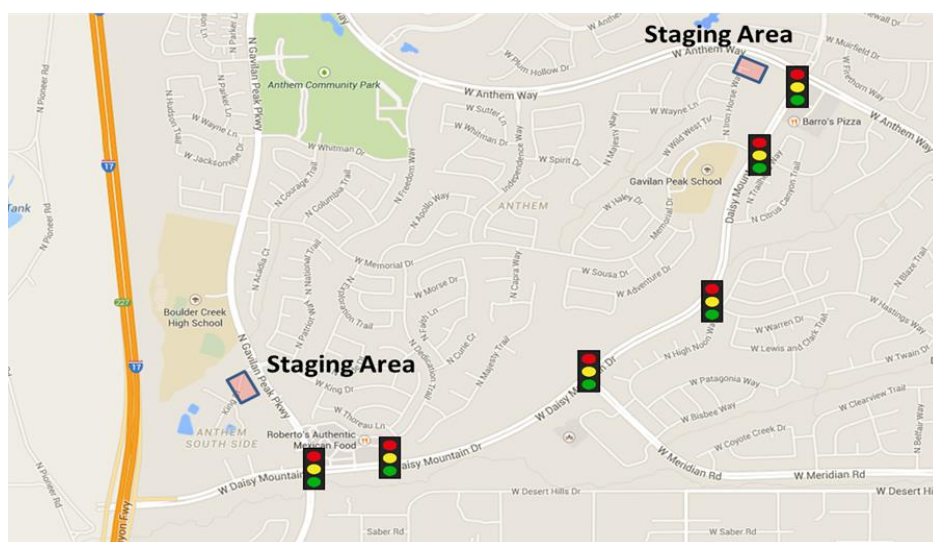


Figure 4-1. Arizona Test Bed (Source: Map data ©2015 Google)

### 4.1.2 GPS Data Collection Procedures

This study utilized portable GPS units to quantify the impact of traffic calming measures on the study corridor. The study utilized a portable Wide Area Augmentation System (WAAS)-enabled GPS receiver to gather second-by-second vehicle trajectories along the study sections. The WAAS-enabled

GPS receiver provides longitude and latitude data to an accuracy of 2.5 m, altitude data to an accuracy of 3 m, and speed measurements to an accuracy of 0.1 m/s.

The GPS used was a BT-Q1000eX 10Hz, manufactured by QSTARZ International Co. This unit is designed to record the date, time, vehicle longitude, vehicle latitude, vehicle altitude, vehicle speed, vehicle heading, and the number of tracking satellites. The system is completely configurable, and the user can change the setup of the DIP switches to select the recording interval from 0.1 s to 5 s as well as the data recording format. The device is operated as a stand-alone unit without the need for a PC or other equipment. Once the GPS unit is powered up, the GPS unit collects the data automatically.

The GPS units were configured to collect time, speed, and location data at 0.1 s intervals. The accelerations were calculated based on the successive second-by-second speed measurements as the first derivative of speed with respect to time. The accuracy of the speed data was examined carefully by using MATLAB code and by manually checking for dropouts and unrealistic speeds. If any unrealistic raw data were found, the trip data were not utilized for the analysis.

A summary of the data collection is provided in Table 4-1. “Base case” (or “MMITSS off”) and “MMITSS on” field data collections were conducted to assess performance of individual MMITSS applications under real-world conditions. GPS floating car travel data were collected on three weekdays in March 2015 to evaluate the Arizona MMITSS applications. Eighteen drivers collected GPS data using 16 test vehicles (8 passenger cars and 10 light duty utility vehicles). The passenger drivers were asked to drive to maintain the traffic stream without any specific instructions about the purpose of the study in order to maintain natural driving patterns. Transit and truck drivers were asked to follow transit vehicles and/or trailer truck driving patterns, to use slow acceleration and deceleration rates, to maintain longer headways than passenger cars, and to refrain from frequent lane changes. A sample driver instruction for FSP data collection is illustrated in Appendix B.

Each driver was instructed to drive their test vehicle according to a scheduled departure plan to maintain a uniform departure rate. For example, five GPS vehicles (using northbound and southbound data collection for the FSP scenario) departed the staging area at Gavilan Peak Parkway at 2-minute intervals. Each driver completed 10 valid round trips for each operational scenario, except for the I-SIG MMITSS scenario, which completed 5 round trips. A significant number of trips were executed (930 trips) during the 3-day field data collection period. It should be noted that any trip that contained unexpected GPS errors and stops was not included as a valid trip. The unexpected stops included any trip that was recorded at the outside of the test route or that contained a long stop (e.g. longer than one minute) at a non-intersection location. Total 906 trip data were utilized for the data analysis.

### 4.1.3 Video Data Collection Procedures

Queue lengths are typically used as an MOE in the evaluation of signal priority projects. If priority is granted, extended green time is taken out of the remaining phases, which are typically side-street phases. Thus, the traffic delay on side streets is the most commonly cited negative impact of the implementation of signal priority systems. Queue length data were recorded by two GoPro video cameras, which were installed at the intersection of Gavilan Peak Parkway and Daisy Mountain Drive. Figure 4-2 shows sample screenshots of video recording data.



(a) Southbound Direction of Gavilan Peak Parkway      (b) Westbound Direction of Daisy Mountain Drive

**Figure 4-2. Still Photos of FSP Queue Data Collection**

**Table 4-1. Field Data Collection Summary**

| Operational Scenarios            | Date                      | Test Vehicle                  | Test Route  | Total Number of Trips (Total 930 Trips)   |
|----------------------------------|---------------------------|-------------------------------|---|---|
| I-SIG MMITSS                     | 3/2/2015 (Monday) p.m.    | 5 OBE and 2 GPS cars          | Northbound (NB) and southbound (SB) at Gavilan Peak Pkwy. and Daisy Mountain Dr. intersection | 25 NB and 25 SB OBE car trips and 10 NB and 10 SB GPS car trips (Total 70 trips)      |
| FSP MMITSS                       | 3/3/2015 (Tuesday) a.m.   | 2 OBE trucks and 5 GPS cars   | NB and SB at Gavilan Peak Pkwy. and Daisy Mountain Dr. intersection                           | 20 NB and 20 SB OBE truck trips and 50 NB and 50 SB GPS car trips (Total 140 trips)   |
|                                  |                           | 5 GPS cars                    | Eastbound (EB) and westbound (WB) at Gavilan Peak Pkwy. and Daisy Mountain Dr. intersection   | 50 EB and 50 WB GPS car trips (Total 100 trips)                                       |
| FSP Base Case                    | 3/4/2015 (Wednesday) a.m. | 1 GPS truck and 4 GPS cars    | NB and SB at Gavilan Peak Pkwy. and Daisy Mountain Dr. intersection                           | 10 NB and 10 SB GPS truck trips and 40 NB and 40 SB GPS car trips (Total 100 trips)   |
|                                  |                           | 4 GPS cars                    | EB and WB at Gavilan Peak Pkwy. and Daisy Mountain Dr. intersection                           | 50 EB and 50 WB GPS car trips (Total 100 trips)                                       |
| Combination of TSP/FSP MMITSS    | 3/3/2015 (Tuesday) p.m.   | 2 OBE trucks and 4 GPS cars   | NB and SB at Gavilan Peak Pkwy. and Daisy Mountain Dr. intersection                           | 20 NB and 20 SB OBE truck trips and 40 NB and 40 SB GPS car trips (Total 120 trips)   |
|                                  |                           | 2 OBE transits and 4 GPS cars | EB and WB on Daisy Mountain Dr. Corridor (six intersections)                                  | 20 EB and 20 WB OBE transit trips and 40 EB and 40 WB GPS car trips (Total 120 trips) |
| Combination of TSP/FSP Base Case | 3/4/2015 (Wednesday) p.m. | 2 GPS trucks and 2 GPS cars   | NB and SB at Gavilan Peak Pkwy. and Daisy Mountain Dr. intersection                           | 20 NB and 20 SB GPS truck trips and 20 NB and 20 SB GPS car trips (Total 80 trips)    |
|                                  |                           | 2 GPS transits                | EB and WB on Daisy Mountain Dr. Corridor (six intersections)                                  | 20 EB and 20 WB GPS transit trips and 30 EB and                                       |

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Intelligent Transportation System Joint Program Office

| Operational Scenarios | Date | Test Vehicle   | Test Route | Total Number of Trips (Total 930 Trips) |
|-----------------------|------|----------------|------------|---|
|                       |      | and 3 GPS cars |            | 30 WB GPS car trips (Total 100 trips)   |

## 4.2 Arizona Field Data Analysis

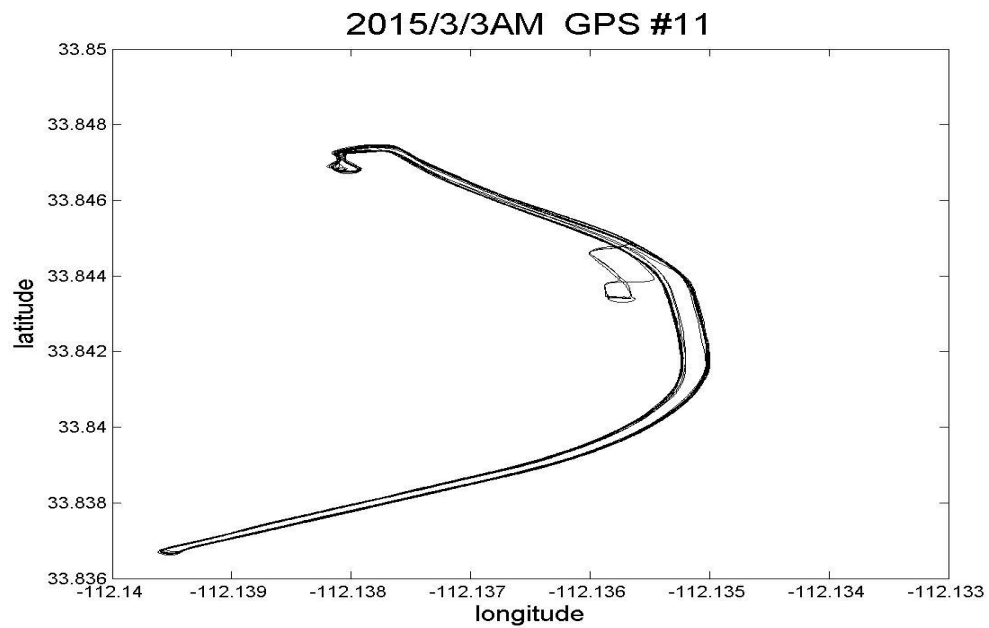
### 4.2.1 FSP Field Data Analysis

The FSP scenario data collection was conducted at the Gavilan Peak Parkway and Daisy Mountain Drive intersection, as illustrated in Figure 4-3. As shown in Table 4-1, 2 OBE trucks and 10 GPS cars were utilized for the FSP tests. Two OBE trucks were operated in the northbound and southbound directions on Gavilan Peak Parkway to evaluate the effectiveness of FSP operation, and 10 GPS vehicles were used to evaluate the impact of unequipped vehicles. In particular, five GPS cars were assigned to northbound and southbound directions to quantify the benefit of unequipped vehicles and another five GPS cars were driven in the eastbound and westbound directions to evaluate the impacts of side-street vehicles. Each driver completed 10 valid round trips based on a trip schedule.

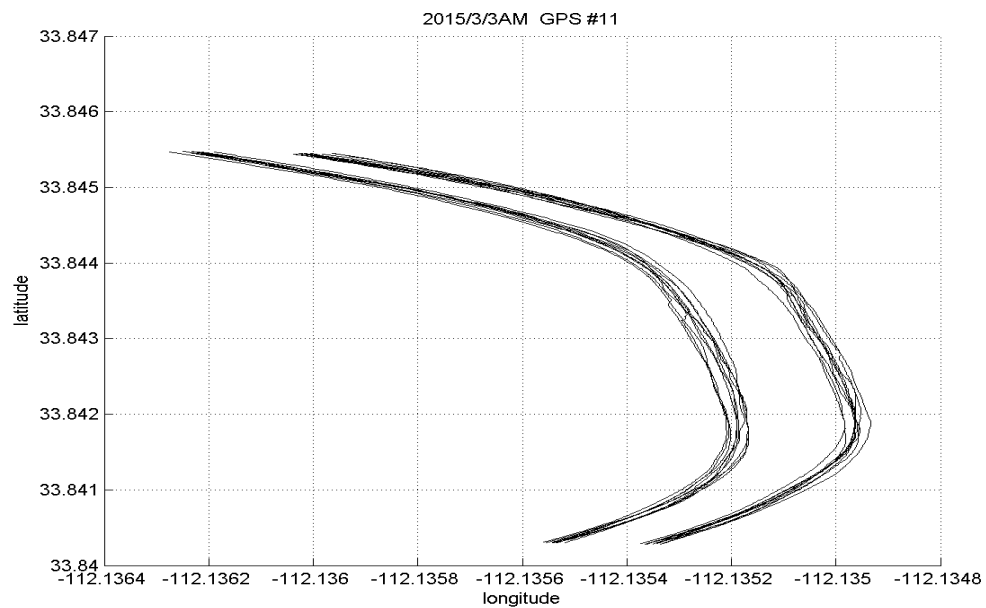


**Figure 4-3. FSP Routes (Source: Map data ©2015 Google)**

Since the GPS data included the entire travel data as illustrated in Figure 4-4, only the portion of a trip that covered the study section was extracted from an entire trip for analysis using a MATLAB code that was developed for this purpose. The software automatically identified the first and last GPS points within the study section using the coordinates of the boundary study sections, as shown in Figure 4-5. Following data reduction, a unique trip number was assigned to each trip. In addition, any unrealistic speed measurements were identified using the MATLAB code and were not used for the study.



**Figure 4-4. Sample GPS Raw Data**



**Figure 4-5. Processed GPS Data**



A time-space diagram, showing 10 sets of southbound trip data for a test vehicle, is presented in Figure 4-6. Zero meters on the y-axis represents the intersection stop line location. The figure shows vehicle operational speeds and stopped durations at the intersection. Typical vehicle operational behaviors at the test intersection are demonstrated in Figure 4-7. The figure illustrates time-space and time-speed diagrams for the no-delay, partially stopped, and fully stopped cases.

Intersection delay for a trip can be computed as the difference in travel time at the instantaneous vehicle speed, versus a hypothetical travel time made at free-flow speeds, as shown in Equation 4-1. The algorithm uses instantaneous free-flow speeds so that, if the free-flow speed changes, the algorithm can reflect these changes. Delay can be computed from a vehicle's origin to its destination. Alternatively, delay can be computed from some distance upstream of the intersection to some distance downstream of the intersection. The total delay is computed as (Ahn, Rakha et al. 2006):

$$d_k = \int_{\alpha}^{\beta} \left[ 1 - \frac{\min(v_f, v_i)}{v_f} \right] \Delta t \quad [4-1]$$

where  $d_k$  is the delay incurred at intersection  $k$ ,  $\Delta t$  is the duration of the time interval (1 second),  $\alpha$  is the time when a test vehicle is at an upstream location (e.g., 100 m) of the intersection,  $\beta$  is the time when the vehicle passes the approach stop bar,  $v_f$  is the free-flow speed, and  $v_i$  is the vehicle speed at instant  $i$ . At the test sites, the study assumed that free-flow speeds were equal to the posted speed limits. The algorithm can also be modified to allow for computation of negative delays when vehicles travel faster than the speed limit.

Mar. 03AM GPS #11 SI #1 SB Trips Time-Space Diagram

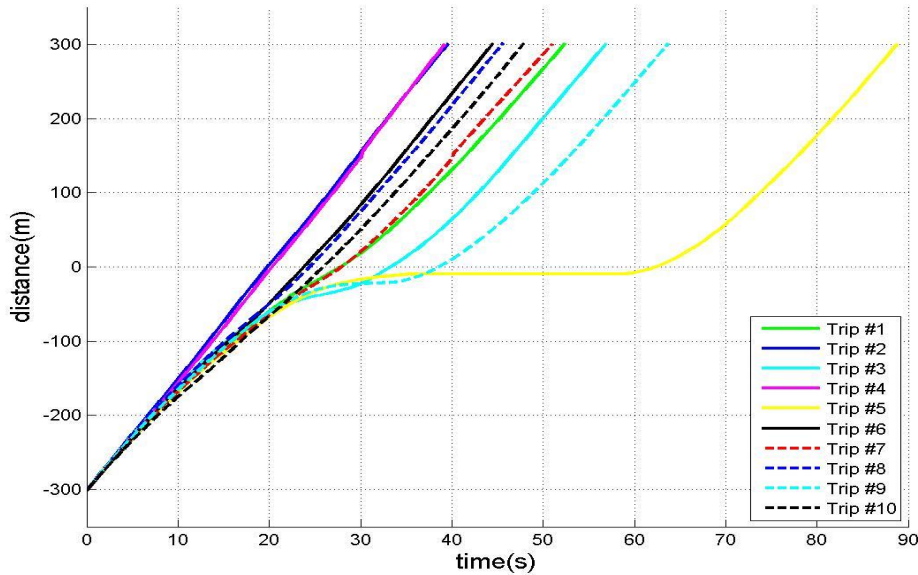
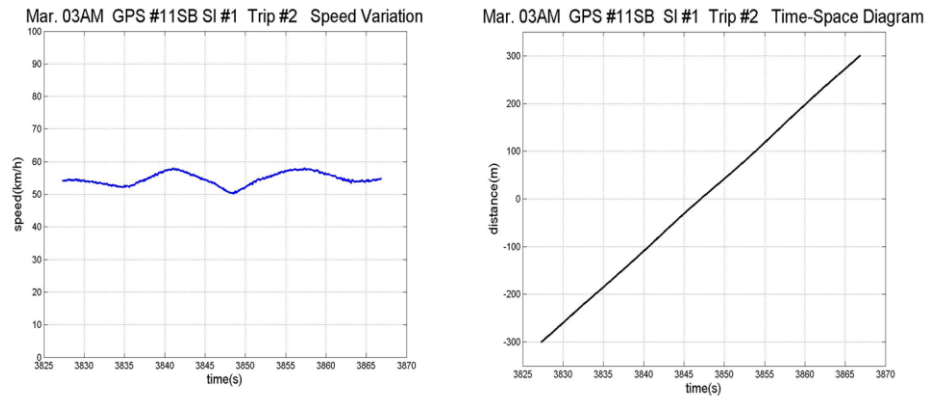
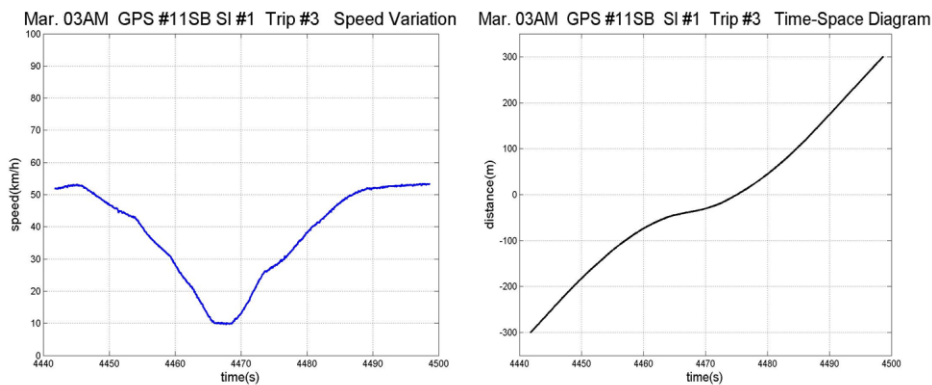


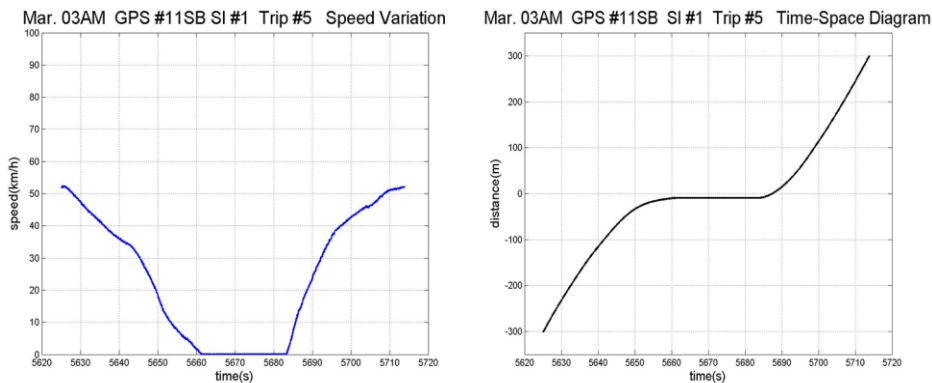
Figure 4-6. Sample Southbound Trip Data



(a) No Delay Case (FSP Scenario)



(b) Partially Stopped Case (FSP Scenario)



(c) Fully Stopped Case (FSP Scenario)

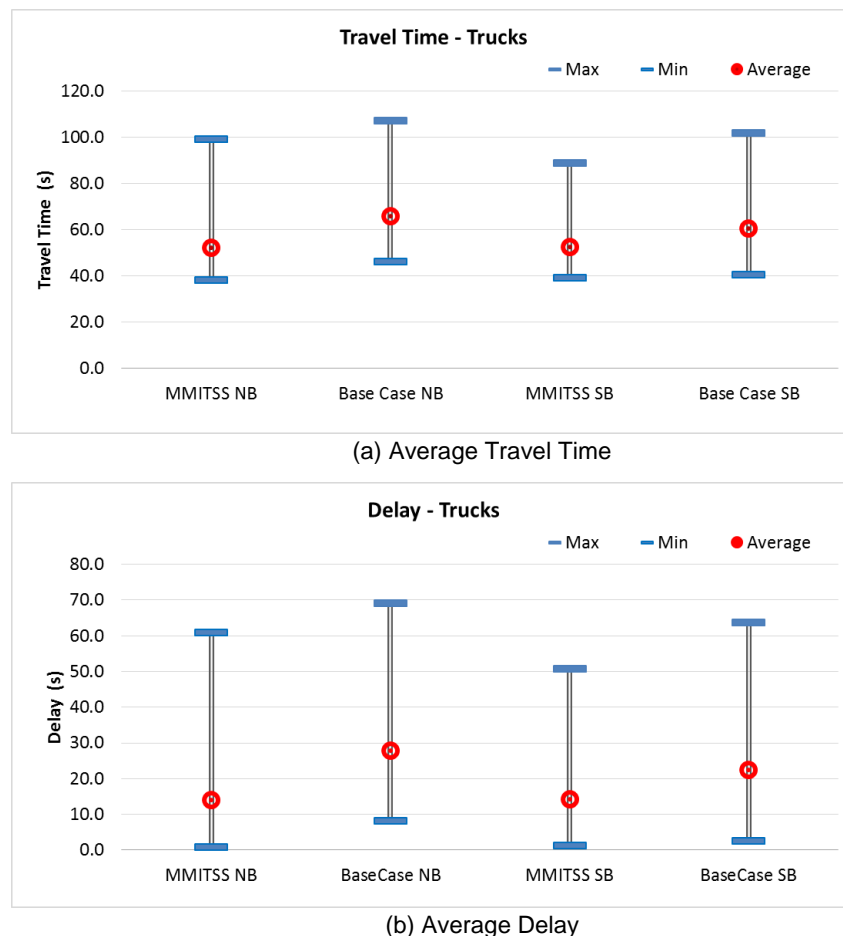
**Figure 4-7. Speed Profiles of Sample Trips**

For the FSP and base case scenarios, Figure 4-8 compares average travel times and average delays for both eastbound and westbound trips. In conducting the intersection travel time and delay analyses, a MATLAB program was written to compute MOEs incurred by vehicles. Travel times and intersection delays were estimated as the difference in travel time between test-vehicle speeds versus free-flow



speeds, starting from 300 m upstream of the intersection stop bar to 300 m downstream of the intersection. The free-flow speed was set at the speed limit (35 mph or 56 km/h) of the test route, Gavilan Peak Parkway.

As shown in Figure 4-8, FSP operations improved northbound and southbound travel times by 20.9 percent and 13.5 percent, respectively, compared with base case operations. The *t*-tests produced *p* values of 0.032 and 0.098, respectively, for northbound and southbound trips. This indicated sufficient evidence that connected trucks reduced northbound travel times, but insufficient evidence to reject the null hypothesis of equal travel times for southbound trips. Furthermore, FSP operations reduced average intersection delay by 49.0 percent and 36.3 percent, respectively, compared with base case operations for northbound and southbound trips. The *t*-test results indicated that FSP operations significantly reduced delay only for northbound trips, with a 0.032 *p* value. The study also found that FSP reduced travel time variability compared with the base case. In particular, the standard deviations for FSP decreased from 19.2 to 16.7 s for northbound trips, and from 20.6 to 13.3 s for southbound trips.



**Figure 4-8. Travel Time and Delay Comparison (FSP Scenarios)**

The study also investigated the impacts of unequipped vehicles during FSP operation, as demonstrated in Table 4-2. The table includes the average delay of unequipped cars for all travel directions: northbound, southbound, eastbound, and westbound. Northbound and southbound trips for unequipped vehicles were made along the same routes that the connected trucks traveled. Eastbound and westbound were the side-street trip directions of FSP operation. Field study results found that FSP operations generally reduced the delay of unequipped vehicles compared with base case operations. In particular, unequipped test vehicles experienced 26 percent and 5 percent delay reductions during northbound and southbound trips, respectively. The *t*-tests were performed on the delay considering a 5-percent significance level, and assuming equal means. Results demonstrated that FSP significantly reduced unequipped vehicle delays for northbound trips, with a 0.037 *p* value. However for southbound trips, the hypothesis was not statistically significant, with a 0.38 *p* value. The study also evaluated side-street delays, which are typically used in the evaluation of signal priority projects. The field data results demonstrate that unequipped vehicles traveling eastbound of the Gavilan Peak Parkway, during FSP operation, experienced delay reductions from 26.1 to 22.8 s (or 12.9%) compared with the base case, but experienced average delay increases of 0.5 s for westbound trips. The *t*-tests produced *p* values of 0.22 and 0.46. This implies insufficient evidence to reject the null hypothesis of equal delay for both eastbound and westbound unequipped vehicle trips. The statistical test indicated that side-street vehicle delays are identical with and without the FSP.

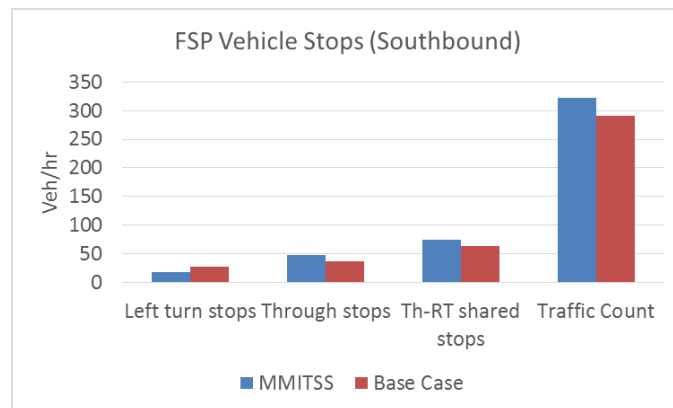
**Table 4-2. The Impacts of FSP for Unequipped Cars**

|                               | Northbound Trip<br>(Truck Movement) |           | Southbound Trip<br>(Truck Movement) |           | Eastbound Trip (Side-Street) |           | Westbound Trip (Side-Street) |           |
|-------------------------------|-------------------------------------|-----------|-------------------------------------|-----------|------------------------------|-----------|------------------------------|-----------|
|                               | MMITSS                              | Base Case | MMITSS                              | Base Case | MMITSS                       | Base Case | MMITSS                       | Base Case |
| <b>Average Delay (s)</b>      | 24.5                                | 33.1      | 17.0                                | 18.1      | 22.8                         | 26.1      | 27.1                         | 26.6      |
| <b>Max. Delay (s)</b>         | 69.4                                | 81.0      | 61.7                                | 56.8      | 71.3                         | 65.6      | 68.9                         | 74.9      |
| <b>Min. Delay (s)</b>         | 0.0                                 | 0.0       | 0.0                                 | 0.0       | 1.3                          | 0.9       | 0.8                          | 2.2       |
| <b>Standard Deviation (s)</b> | 22.2                                | 21.8      | 17.5                                | 16.2      | 20.7                         | 19.3      | 19.5                         | 18.1      |
| <b>Relative Difference</b>    | 26.0%                               |           | 6.0%                                |           | 12.9%                        |           | -1.6%                        |           |

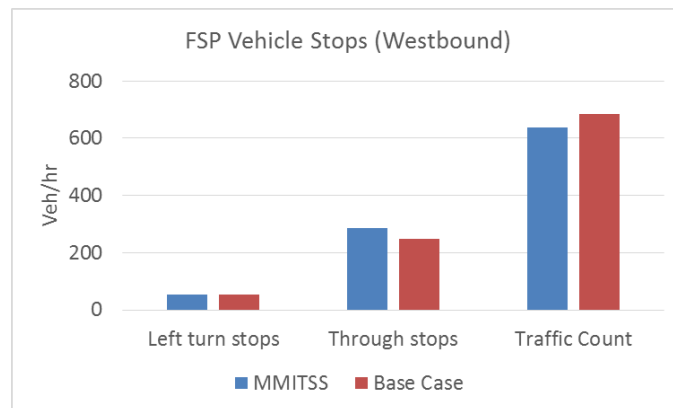
The study also used recorded video to assess FSP impacts. Recordings were made for the test intersection's southbound and eastbound approaches. Test trucks traveled in the northbound and southbound directions. Thus, the southbound traffic was recorded to obtain truck movements, while the westbound approach was used to capture side-street traffic flow.

Following data collection, vehicle counts and vehicle stops were manually counted. Figure 4-9 shows the number of vehicle stops and the percentage of vehicle stops with and without FSP. The figure demonstrates that FSP did not affect the number of stops on the truck movement approach. In particular, the results show that more vehicles stopped at the stop line with FSP due to higher traffic volumes during the MMITSS data collection period. The field-collected data also suggest that FSP increases the number of stops for the side street. The figure shows that 53.5 percent of side-street

vehicles were stopped at the traffic signal under FSP operations, while 44.0 percent of side-street vehicles were stopped without FSP operations.



(a) Southbound Approach



(b) Westbound Approach

**Figure 4-9. FSP Vehicle Stops Analysis from Video Recorded Data**

## 4.2.2 Combination of TSP and FSP Field Data Analysis

The IA study evaluated the impacts of deploying MMITSS applications and strategies under various operational conditions. In particular, the effort investigated broader impacts of individual applications, logical combinations of bundles, and synergistic impacts.

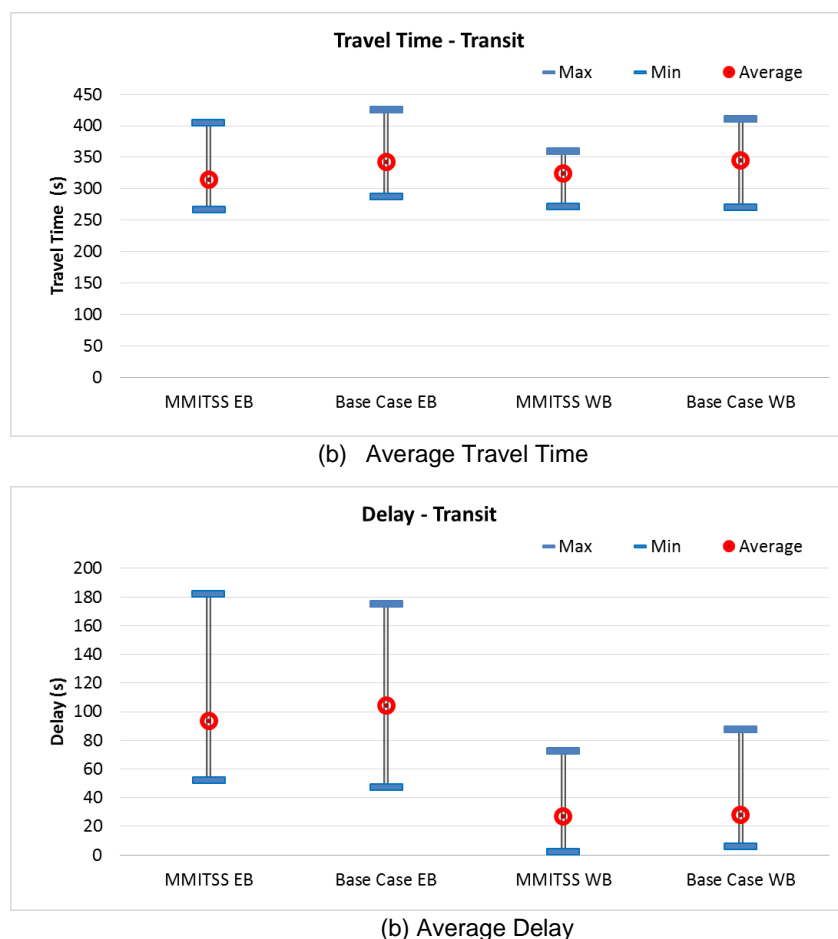
The MMITSS system is capable of processing multiple requests for priority that may be received from multiple vehicles, as well as multiple modes, at any time. The combination of TSP and FSP applications can process multiple priority requests from connected transit vehicles and from connected trucks.

Data collection for the FSP scenario was conducted at six signalized intersections along Daisy Mountain Drive. Figure 4-10 illustrates these six intersections, plus the test routes used for transit, truck, and unequipped vehicles. Data collection details for the scenario are summarized in Table 4-1. For the combination of TSP and FSP applications, two OBE trucks, two OBE transits, and eight GPS cars were utilized for the field data collection. Data were collected for a total of 240 vehicle trips. For the base case scenario, 2 GPS trucks, 2 GPS transits, and 5 GPS cars collected data for 180 vehicle trips. Transit vehicles completed eastbound and westbound trips on the study corridor and trucks operated along the northbound and southbound directions on Gavilan Peak Parkway. For the field data collection, both connected trucks and connected transit vehicles were given the same priority level and 1:1 weight factors were given to trucks and buses, respectively.



**Figure 4-10. Routes of the Combination of TSP and FSP Applications (Source: Map data ©2015 Google)**

For connected transit vehicles within the MMITSS and base case scenarios, Figure 4-11 compares average travel times and delays for eastbound and westbound trips. Field-collected data indicate that the MMITSS operations improved transit travel times by 8.2 percent and 6.1 percent for eastbound and westbound trips, respectively, compared with base case operations. Statistical tests produced  $p$  values of 0.017 and 0.032, respectively, for eastbound and westbound transit trips. This indicates sufficient evidence that connected transit vehicles reduce travel time. The figure also shows that the MMITSS operations reduced transit delays by up to 10.5 percent. Specifically, MMITSS applications reduced transit delays from 104.6 to 93.6 s for eastbound trips, and from 28.1 to 26.7 s for westbound trips. Eastbound trip delays were considerably higher because the eastbound approach was more congested than the westbound approach during the afternoon data collection period.



**Figure 4-11. Travel Time and Delay for Transit Vehicles (Combination of TSP/FSP)**

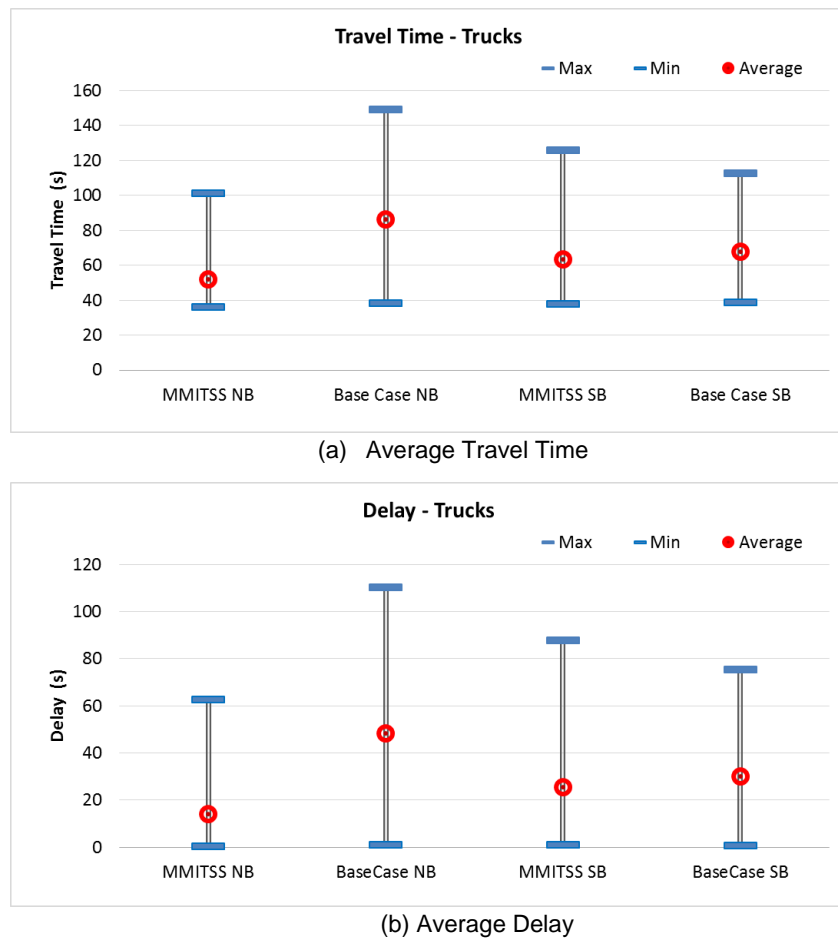
Table 4-3 compares overall intersection delays, with and without the combination of TSP and FSP applications, for trucks and cars. For eastbound trips, relatively high intersection delays were observed at the Gavilan Peak, Dedication, and Anthem Way intersections. Except for the Anthem Way intersection, field-collected data showed that for eastbound trips, connected transit vehicles effectively reduced intersection delays. Specifically, MMITSS reduced eastbound approach delays by 16.8 percent, 20.5 percent, 24.6 percent, 22.6 percent, and 41.3 percent at the Gavilan Peak, Dedication, Meridian, Hastings, and Memorial intersections. Connected transit vehicles also reduced westbound trip delays by 4.7 percent. The study also found that unequipped cars benefited from MMITSS operations. The unequipped vehicles experienced 3.1 percent and 1.5 percent reductions in eastbound and westbound travel time, respectively. The table shows that for westbound trips, MMITSS reduced the travel time but increased intersection delays for unequipped vehicles. The increased delay was caused by the delay estimation method. The intersection delay is measured when a test vehicle enters a section 300 m upstream of an intersection but the travel time is measured for the entire study section. Thus, if a test vehicle is operated at high speed during a trip, it can reduce the travel time but increase the delays at some intersections.

**Table 4-3. Intersection Delays for Transit Vehicles and Passenger Cars (Combination of TSP/FSP Applications)**

|                 |   | Travel Times | Delay Total | Delay – Gavilan Peak | Delay – Dedication | Delay – Meridian | Delay – Hastings | Delay – Memorial | Delay – Anthem Way |
|-----------------|---|--------------|-------------|----------------------|--------------------|------------------|------------------|------------------|--------------------|
| <b>EB Trips</b> | <b>MMITSS Connected Transit (s)</b>     | 314.83       | 93.55       | 18.95                | 29.69              | 5.62             | 5.54             | 2.87             | 30.89              |
|                 | <b>Base Case Unequipped Transit (s)</b> | 342.99       | 104.56      | 22.77                | 37.33              | 7.45             | 7.15             | 4.90             | 24.96              |
|                 | <b>Relative Difference</b>              | 8.2%         | 10.5%       | 16.8%                | 20.5%              | 24.6%            | 22.6%            | 41.3%            | -23.8%             |
|                 | <b>MMITSS Unequipped Car (s)</b>        | 254.81       | 54.24       | 17.62                | 4.75               | 4.69             | 1.70             | 5.04             | 20.44              |
|                 | <b>Base Case Unequipped Car (s)</b>     | 263.01       | 69.76       | 22.24                | 5.40               | 2.73             | 3.20             | 3.40             | 32.80              |
|                 | <b>Relative Difference</b>              | 3.1%         | 22.2%       | 20.8%                | 12.1%              | -72.0%           | 46.8%            | -48.5%           | 37.7%              |
| <b>WB Trips</b> | <b>MMITSS Connected Transit (s)</b>     | 324.14       | 26.75       | 11.82                | 0.72               | 2.77             | 2.48             | 8.95             | n/a                |
|                 | <b>Base Case Unequipped Transit (s)</b> | 345.05       | 28.06       | 14.85                | 3.73               | 1.44             | 0.65             | 7.39             | n/a                |
|                 | <b>Relative Difference</b>              | 6.1%         | 4.7%        | 20.4%                | 80.6%              | -92.2%           | -284%            | -21.1%           | n/a                |
|                 | <b>MMITSS Unequipped Car (s)</b>        | 250.51       | 36.72       | 17.16                | 3.48               | 2.28             | 3.31             | 10.49            | n/a                |
|                 | <b>Base Case Unequipped Car (s)</b>     | 254.39       | 30.85       | 18.36                | 4.09               | 0.69             | 2.83             | 4.87             | n/a                |
|                 | <b>Relative Difference</b>              | 1.5%         | -19.0%      | 6.6%                 | 15.0%              | -229%            | -16.9%           | -115.4%          | n/a                |

The study also investigated MMITSS impacts for connected trucks and unequipped cars that traveled on northbound and southbound approaches of the Gavilan Peak intersection, as illustrated in Figure 4-12 and Table 4-4. Field data results indicate that MMITSS applications reduced northbound and southbound connected truck travel times by 39.7 percent and 6.8 percent. Moreover, northbound and southbound connected truck delays were reduced by 70.8 percent and 16.0 percent. The *t-test* results indicate that FSP operations significantly reduced travel times and delays for northbound connected trucks (with 0.001 and 0.000 *p* values). However, southbound connected truck travel time and delay reductions were found to not be statistically significant (with 0.28 and 0.27 *p* values). Although MMITSS applications reduced travel times (6.5 percent and 2.7%) and delays (13.9% and 7.4%) for

unequipped cars, *t*-tests indicated insufficient evidence of significant travel time and delay reductions for such vehicles.

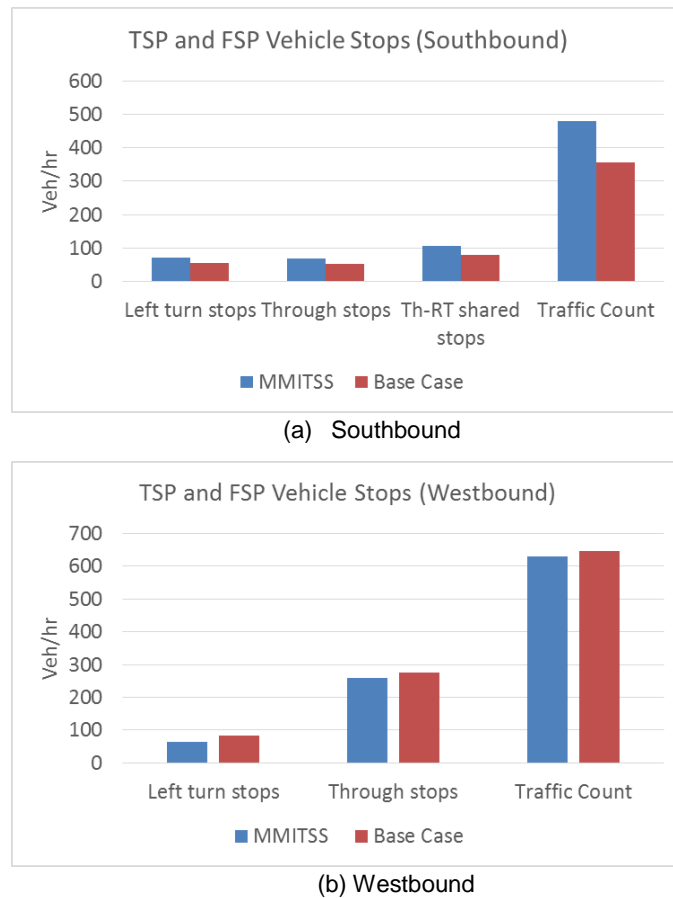


**Figure 4-12. Travel Time and Delay Comparison for Trucks (Combination of TSP/FSP Applications)**

**Table 4-4. Travel Time and Delay for Unequipped Cars (Combination of TSP/FSP Applications)**

|                   | Travel Time |              |           |              | Delay     |              |           |              |
|-------------------|-------------|--------------|-----------|--------------|-----------|--------------|-----------|--------------|
|                   | MMITSS NB   | Base Case NB | MMITSS SB | Base Case SB | MMITSS NB | Base Case NB | MMITSS SB | Base Case SB |
| <b>Maximum</b>    | 125.6       | 122.3        | 115.1     | 130.6        | 89.0      | 88.1         | 77.5      | 93.9         |
| <b>Minimum</b>    | 34.4        | 37.5         | 34.2      | 31.4         | 0.0       | 1.3          | 0.0       | 0.0          |
| <b>Average</b>    | 62.6        | 67.0         | 59.0      | 60.7         | 25.4      | 29.5         | 22.3      | 24.0         |
| <b>Difference</b> | 6.5%        |              | 2.7%      |              | 13.9%     |              | 7.4%      |              |

The number and percentage of vehicle stops obtained from video data are illustrated in Figure 4-13. While GPS trip data can evaluate the performance of test vehicles, the video data investigated MMITSS impacts for all vehicles at the intersection. At the Gavilan Peak and Daisy Mountain intersections, the southbound and eastbound approaches were recorded on video. Results demonstrated that MMITSS marginally reduced vehicle stops (from 52.3% to 51.3% for southbound vehicles, and from 55.5% to 50.9% for westbound vehicles).



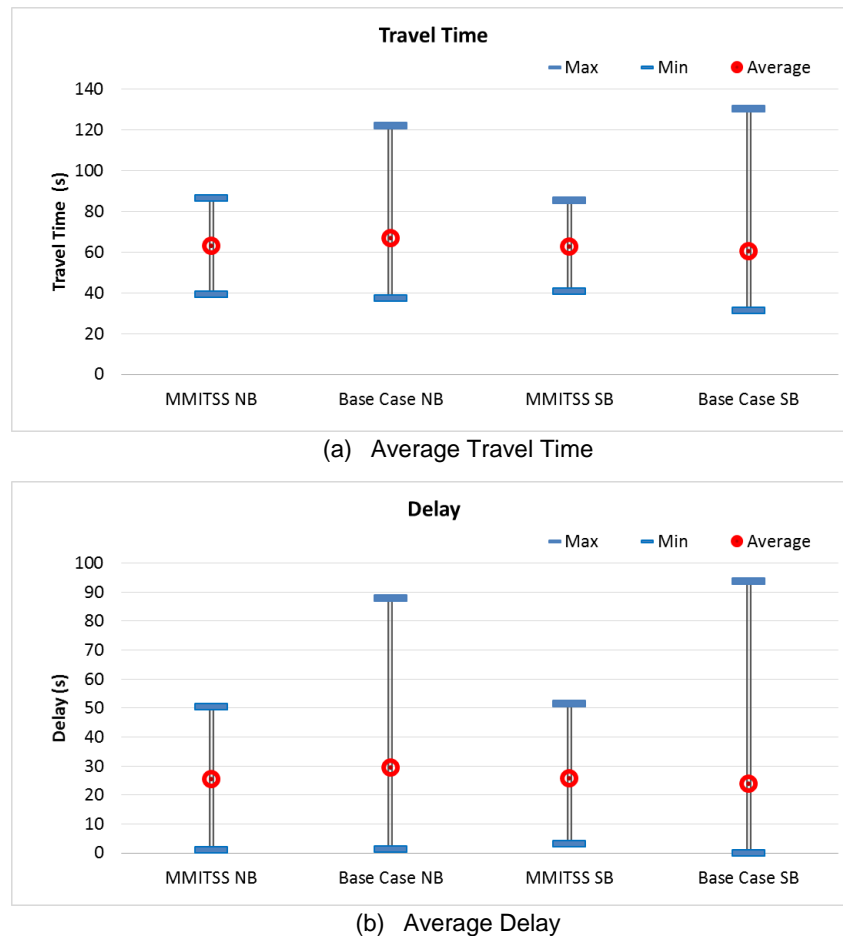
**Figure 4-13. Vehicle Stops Analysis from Video Recorded Data (Combination of TSP/FSP Applications)**

### 4.2.3 I-SIG Application Data Analysis

For the I-SIG scenario, data collection was conducted at the Gavilan Peak Parkway and Daisy Mountain Drive Intersection, illustrated in Figure 4-3. Five OBE cars and two GPS cars were utilized. Test vehicles were operated in the northbound and southbound directions of Gavilan Peak Parkway. For base case testing, trips were collected from two GPS cars. The study analyzed a total of 70



vehicle trips for I-SIG, and 40 trips for the base case. Results indicate that I-SIG improved northbound travel times and intersection delays from 67.0 to 63.2 s and from 29.5 to 25.5 s, illustrated in Figure 4-14. However, I-SIG increased southbound travel times and delays from 60.7 to 62.9 s and from 24.0 to 25.7 s. The *t*-tests were performed on travel time and delay data, considering a 5-percent significance level, and assuming equal means. Results demonstrated that the hypothesis was not statistically significant, with *p* values between 0.23 and 0.38. However, the figure shows I-SIG considerably reduced travel time reliability compared with the base case. In particular, standard deviations of I-SIG decreased from 26.9 to 11.7 s and from 26.3 to 12.6 s for northbound and southbound trips. It was concluded that even without significant travel time increases or decreases, I-SIG improved travel time reliability by up to 56 percent.



**Figure 4-14. Travel Time and Delay for Unequipped Cars (I-SIG)**

## 4.3 Arizona Simulation Model

### 4.3.1 Arizona Simulation Model Description

The field evaluation study quantified the benefits of MMITSS applications. However, system-wide impacts of MMITSS could not be observed due to limitations and constraints in the field data collection. Therefore, simulation studies were conducted to quantify MMITSS deployment impacts under a wider variety of operational conditions. The VISSIM microscopic traffic simulation software was used to evaluate system-wide benefits of MMITSS. The PD team developed an Arizona simulation model in VISSIM 6, using the Econolite ASC3 virtual signal controller. The IA team calibrated the VISSIM model using field-collected data.

The simulation study reflected traffic count and turning movement data provided by the Maricopa Department of Transportation (MCDOT). Traffic data during morning, midday, and afternoon peak periods were available in the data file format of SYNCHRO, a software package for modeling and optimizing traffic signal timings. The simulation study utilized traffic count data during one hour of the morning peak period. Volume capacity ratio (V/C) is a commonly-used index for conveying congestion levels. Morning peak period demands in the Arizona test corridor produced V/C equal to 0.5, indicating that test intersections were operating under capacity, with no excessive delays. Traffic demand inputs within the VISSIM model were then proportionally increased to obtain scenarios for V/C equal to 0.85 and V/C equal to 1.0.

The simulation model was calibrated by using information derived from field data collection. This information included free-flow speeds, saturation flow rates, vehicle speed distributions, and acceleration distributions. Vehicle type characteristics were adjusted to represent real-world conditions. In particular length, width, power distribution, and weight distribution were updated to represent realistic dynamics of trucks. Further, the car-following model was calibrated to reflect field-measured saturation flow rates. Specifically, the Wiedemann 74 model was utilized to represent an arterial road, and was calibrated to produce a saturation flow rate of 1,800 vehicles/hour/lane. Each simulation scenario was repeated five times with a different random seed, in order to capture stochastic properties of the VISSIM software.

### 4.3.2 Arizona I-SIG Simulation Results

The simulation study investigated system-wide impacts of I-SIG, which could not be quantified in the previous field study. Figure 4-15 compares the system-wide delay and average speed. The combinations of three congestion levels and three different CV market penetration rates (MPRs) were investigated to estimate the most beneficial conditions. As illustrated in the figure, I-SIG implementation significantly improved overall traffic operations. In particular, I-SIG reduced vehicle delay by up to 20.6 percent when compared with the base case (i.e., actuated traffic control system). The simulation study found that I-SIG reduced vehicle delays by 15.8 percent, 17.4 percent, and 10 percent for V/C ratios 0.5, 0.85, and 1.0, respectively. These V/C ratios represent uncongested, near-congested, and congestion conditions. The study also found that the CV MPRs of 25 percent, 50

percent, and 75 percent reduced vehicle delays by 11.8 percent, 15.9 percent, and 15.4 percent. Therefore a CV MPR of 75 percent did not significantly improve performance compared with a CV MPR of 50 percent on the Arizona test facility.

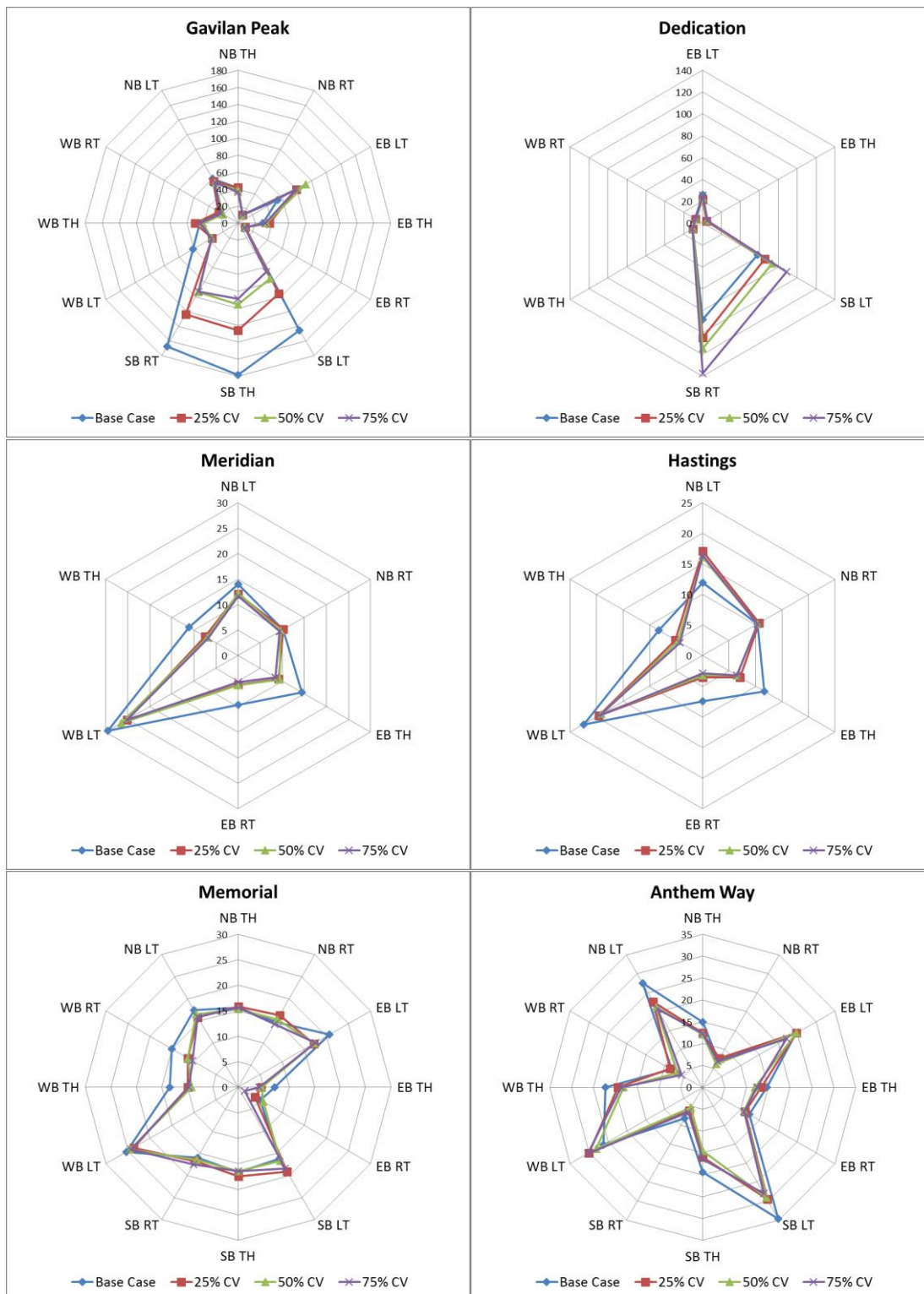
The Arizona simulation study also evaluated impacts of I-SIG on average vehicle speeds, as illustrated in Figure 4-15. The study found that I-SIG increased average speeds by 4.7 percent, 10.1 percent, and 6.5 percent for V/C ratios of 0.5, 0.85, and 1.0, compared with the actuated system. Also, CV MPRs of 50 percent and 75 percent improved average vehicle speeds by 7.9 percent and 7.7 percent, while a CV MPR of 25 percent increased vehicle speeds by 5.8 percent, compared with the base case scenarios. The study found that the optimum condition for operating I-SIG was the V/C ratio 0.85, with CV MPRs of 50 percent or 75 percent. Under these conditions, I-SIG achieved vehicle delay reductions and speed increases of 20.6 percent and 11.9 percent, respectively.



**Figure 4-15. Delay and Speed Comparison in the Arizona I-SIG Scenarios**

The study also investigated traffic movement delays for all six intersections and various CV MPR scenarios, as illustrated in Figure 4-16. The figure shows radar diagrams for all six intersections. The simulation results demonstrate that I-SIG operation effectively reduced delays compared with the base case scenario. At the Gavilan Peak intersection, I-SIG reduced delay by up to 11.8 percent and

50.3 percent for the northbound and southbound through movements, respectively. However at the same intersection, the delay in eastbound through movement was increased by up to 26.1 percent. The I-SIG algorithm assigns green durations based on vehicle delay and volume. The simulation results imply that I-SIG reallocates signal phase times to reduce the system-wide intersection delays. The figure also shows that I-SIG increases southbound approach delays at the Dedication intersection when the CV MPR increases. When the market penetration increases, I-SIG assigns more green time to eastbound and westbound traffic to improve the system-wide performance, causing the increased southbound approach delays.



**Figure 4-16. Intersection Delay for the Arizona I-SIG Scenarios (V/C 0.85)**

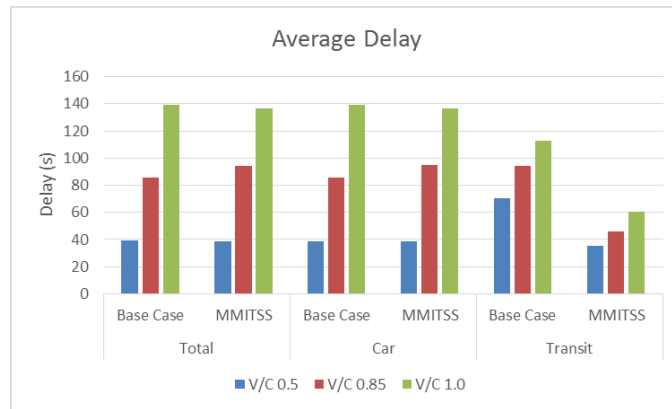
### 4.3.3 Arizona TSP Simulation Model Results

This section presents the system-wide impacts of TSP at various congestion levels. Varying the congestion level could produce different results and possibly identify congestion levels for which TSP can be effectively operated. To quantify the impacts of TSP for various congestion levels, transit demands in the simulation model were set to 2 percent of eastbound and westbound traffic flows. Thus, all transit vehicles traveled from the eastern to western (or western to eastern) end of the study corridor without turning movements. In scenarios of increasing corridor congestion, the number of transit vehicles increased proportionally. All transit vehicles (2% of the eastbound and westbound traffic) were simulated as equipped vehicles, and all other cars were unequipped. However, in the base case scenarios, the simulation study assumed that all transit and cars were unequipped.

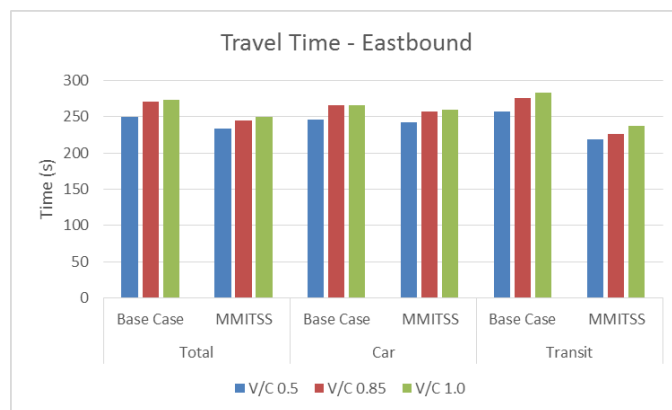
Figure 4-17 compares the average delay of transit vehicles and general traffic with and without TSP operation at various traffic demands. In particular, the simulation results demonstrated that the transit vehicles experienced 49.9 percent, 51.4 percent, and 46.4 percent delay reductions with TSP for V/C ratios 0.5, 0.85, and 1, respectively. TSP operations marginally reduced average delays by 0.6 percent and 2.2 percent for V/C ratios 0.5 and 1, respectively. However, TSP increased delays by 10.6 percent when the V/C ratio was 0.85. If transit priority is granted, extended green time is taken out of remaining phases, which typically provide green times for side streets. Thus, traffic delay on side streets is the most commonly cited negative impact of TSP systems and may increase system-wide vehicle delay.

The study also investigated travel times for transit vehicles and passenger cars, with and without TSP. The analysis focused on travel times for westbound and eastbound vehicles, which only traveled between eastern and western ends of the study corridor. The simulation results (Figure 4-18) demonstrated that for eastbound and westbound traffic, TSP reduced travel times for both transit and passenger vehicles on Daisy Mountain Drive. In particular, TSP reduced eastbound travel times for connected transit vehicles by 14.8 percent, 18.0 percent, and 16.1 percent for V/C ratios 0.5, 0.85, and 1, respectively. Similarly, at V/C levels of 1.0, westbound transit vehicles reduced travel times up to 27.8 percent. The figure also demonstrates that eastbound and westbound passenger cars experienced travel time reductions of 3.2 percent and 17.5 percent (respectively) at all congestion levels due to TSP operation. The simulation results indicate that TSP effectively saves travel time for both transit and passenger vehicles on the corridor where TSP is operated but may increase system-wide delay due to reduced green times on the side streets. Given the limited simulation scenarios and specific network conditions, the maximum benefit of connected transit vehicles under TSP operation was observed at a V/C of 1.0, with travel time savings of 27.8 percent.

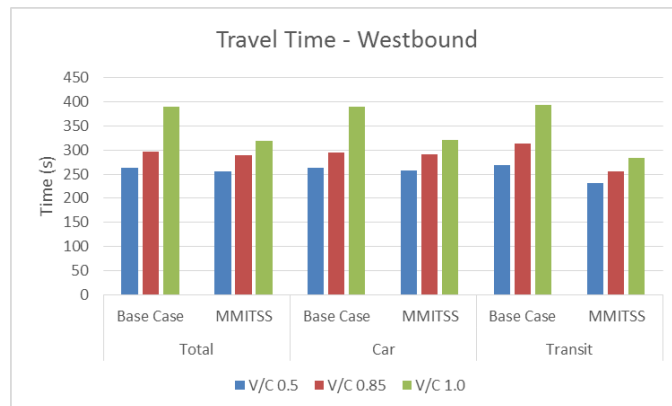
Figure 4-19 illustrates the intersection movement delays at all six intersections. The figure demonstrates that TSP reduced transit movement delays but increased side-street delays. In particular, eastbound and westbound delays at Gavilan Peak were reduced by 14.6 percent and 5.7 percent, but northbound and southbound delays were increased by 11.8 percent and 11.1 percent, respectively. These simulation results indicate that TSP operation effectively accommodates transit vehicles, but may increase side-street delays.



**Figure 4-17. Delay Comparison in the Arizona TSP Scenarios**



**(a) Eastbound Corridor Travel Time**



**(b) Westbound Corridor Travel Time**

**Figure 4-18. Travel Time Comparison in the Arizona TSP Scenarios**

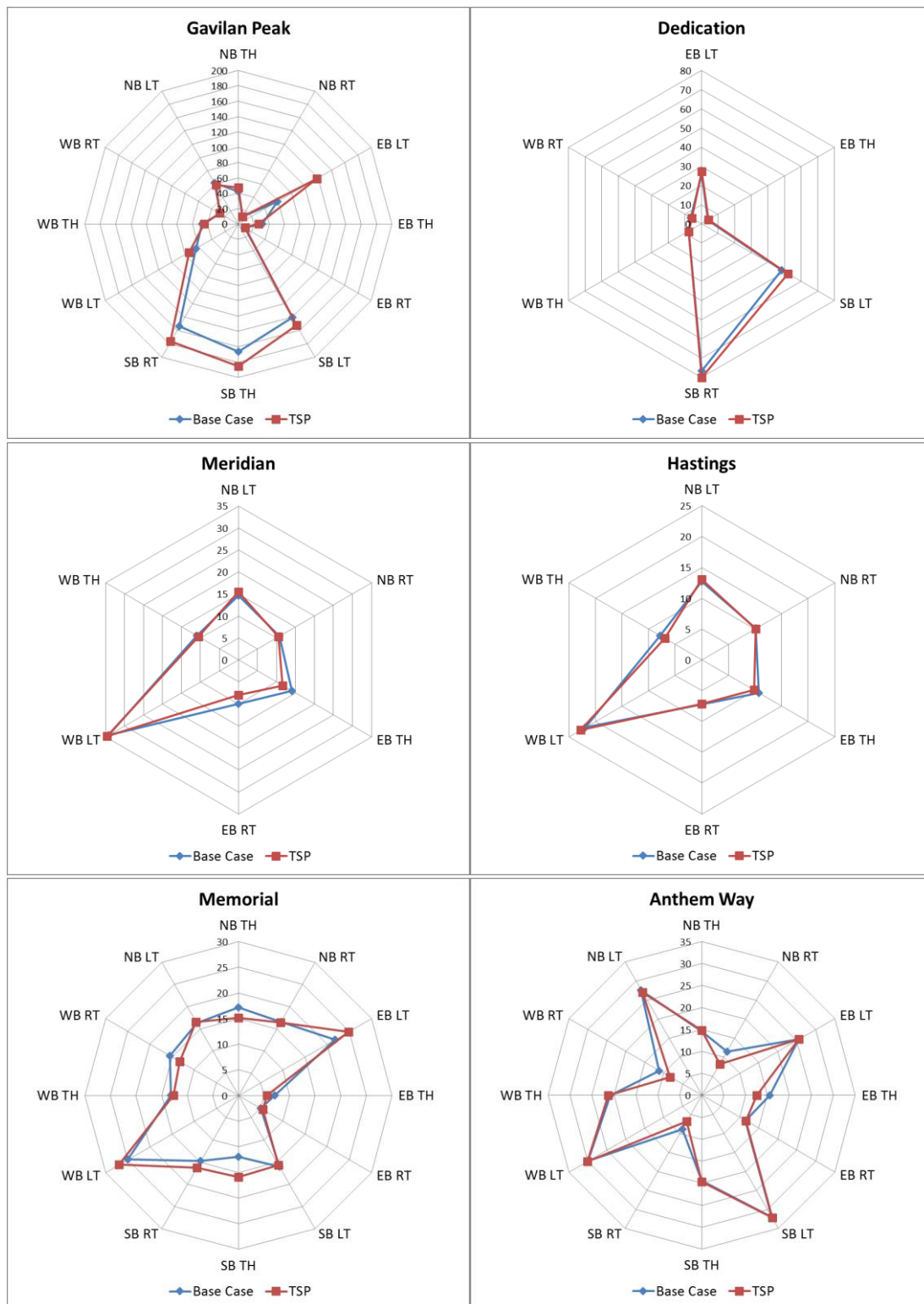


Figure 4-19. Intersection Delay for the Arizona TSP Scenarios (V/C 0.85)



### 4.3.4 Arizona FSP Simulation Model Results

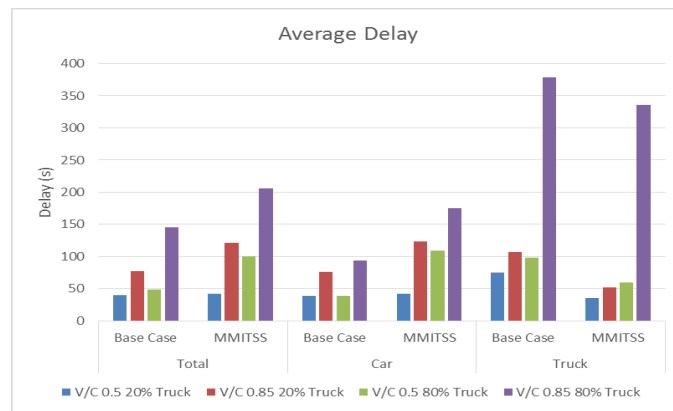
The FSP application provides traffic signal priority for freight and commercial vehicles in a signalized network. The microscopic traffic simulation study investigated system-wide impacts of FSP on the Arizona test network by modeling the test corridor as a major freight route.

Similar to the TSP study, trucks were only allowed to travel between the eastern and western ends of the study corridor, and were not allowed to make turning movements. The study investigated system-wide impacts of FSP for two congestion levels (V/C of 0.5 and 0.85), and for two truck composition rates (20% and 80%). In the MMITSS-on scenarios, all trucks were modeled as equipped vehicles, while all other cars were unequipped. In the MMITSS-off (base case) scenarios, all vehicles (including trucks) were modeled as unequipped vehicles.

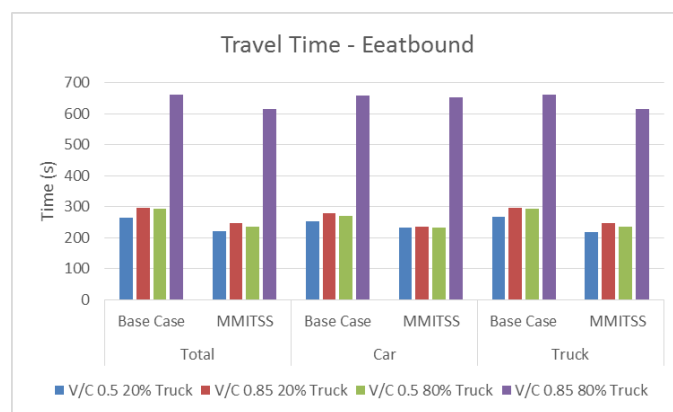
Figure 4-20 compares the system-wide delay of freight vehicles and general traffic, with and without FSP operation, for various operational scenarios. Simulation results indicate that the provision of FSP reduced truck delay by up to 53 percent compared with the base case scenarios. Specifically, equipped trucks experienced 52.4 percent and 25.0 percent reductions in average delay for the 20-percent and 80-percent truck composition scenarios, respectively. Thus, the FSP application performed more effectively for a 20-percent truck composition than for higher truck volumes in the Arizona network. While FSP significantly reduced truck delay, system-wide delay of the network was increased substantially, especially in the 80-percent truck composition scenario. Similar to the TSP case, the extended green time for truck routes shortened green times on the side streets. This caused heavy congestion on the side streets and caused system-wide performance to deteriorate.

The travel times of trucks and passenger cars, with and without FSP operation, are illustrated in Figure 4-21. Similar to the TSP analysis, only eastbound and westbound corridor trips were considered in the travel time comparison. According to the simulation results, FSP constantly reduced truck travel times relative to the base case scenarios. In particular, trucks experienced 20.5 percent lower travel times under FSP, while unequipped passenger cars experienced 19.8 percent reductions in travel time. The figure also demonstrated that significantly high travel times were observed for the eastbound trips with a V/C of 0.85 and a truck composition of 80 percent. These high travel times were caused by the geometric design of the Arizona network, which could not manage a high truck demand and triggered significant delay at the end of the study corridor.

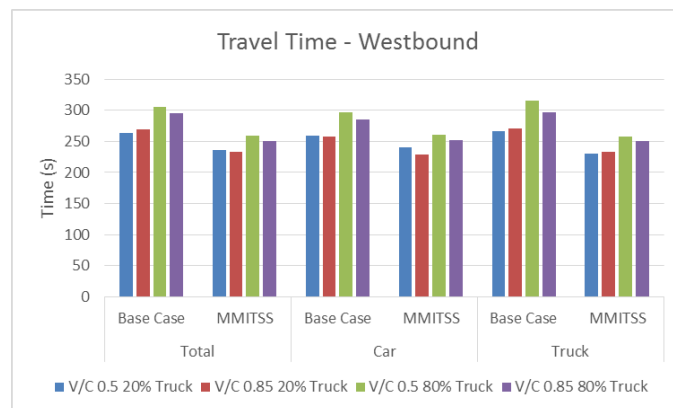
In summary, the simulation results indicated that FSP successfully reduced travel times by up to 20.5 percent and reduced delays by up to 53 percent for connected trucks. However, the FSP application also increased system-wide delay due to the increased delays on side streets. It should be noted that, because the simulation results were based on a specific set of network conditions in Arizona, FSP could produce different results in another network environment.



**Figure 4-20. Delay Comparison in the Arizona FSP Scenarios**



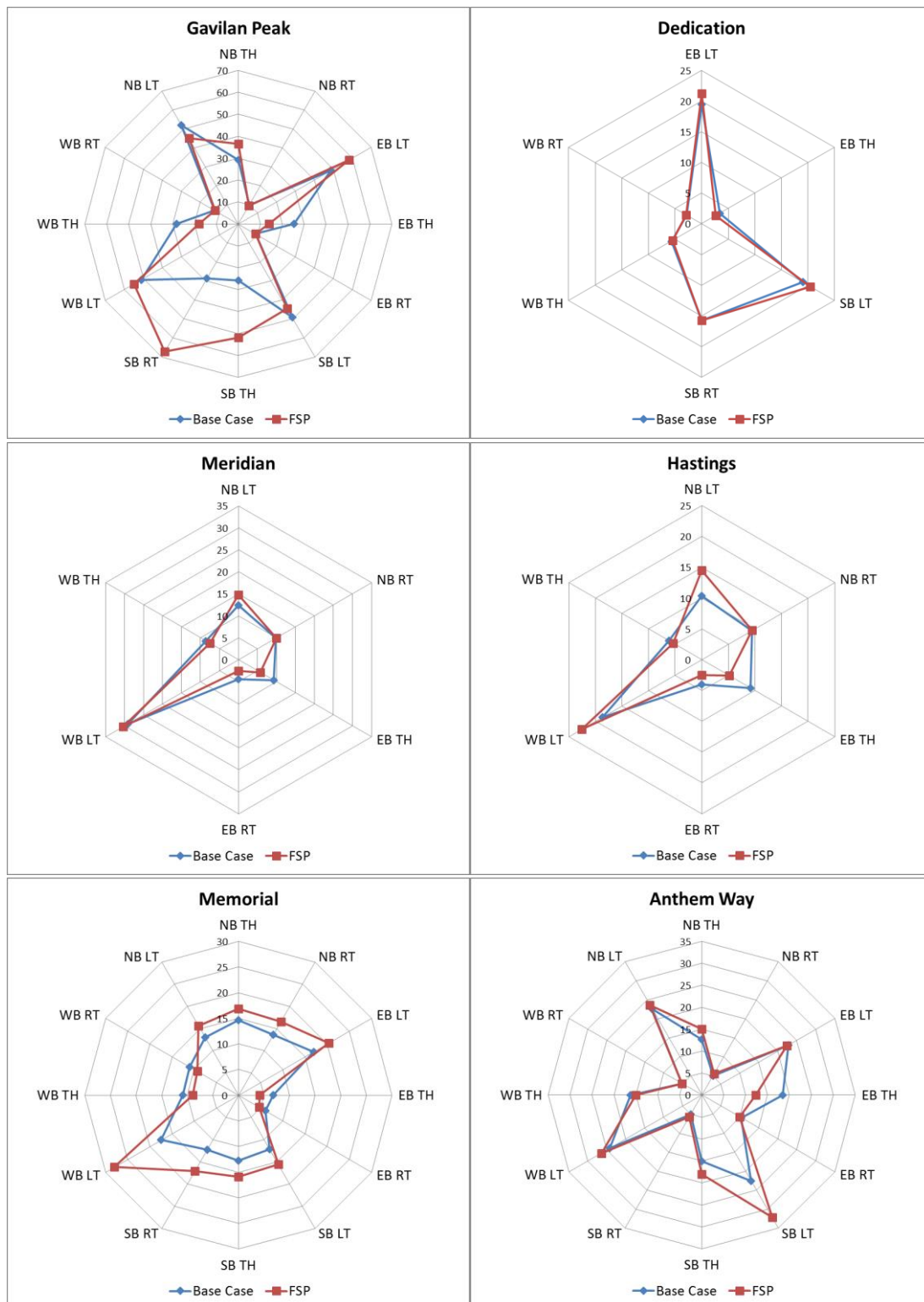
**(a) Eastbound Corridor Travel Time**



**(b) Westbound Corridor Travel Time**

**Figure 4-21. Travel Time Comparison in the Arizona FSP Scenarios**

Figure 4-22 compares the average vehicle delays for each movement with and without FSP operation. The radar diagrams demonstrate that FSP effectively gives priority to traffic signal approaches when trucks are detected, but also increases side-street delays. In particular, FSP reduced eastbound and westbound through movement delays by 45.2 percent and 36 percent, but increased northbound and southbound through movement delays by 24.9 percent and 100.9 percent, respectively, at Gavilan Peak. The results indicate that while FSP can improve freight movement, FSP implementation should be carefully examined because it may adversely affect system-wide performance due to increased side-street delays.



**Figure 4-22. Intersection Delay for the Arizona FSP Scenarios (V/C 0.50 with 20% Trucks)**

### 4.3.5 Arizona TSP and FSP Combination Simulation Model Results

This section describes the investigation of system-wide impacts from the combination of TSP and FSP applications. The overall objective of the MMITSS scenario is to improve system mobility across multiple modes at signalized intersections. In particular, the study assessed overall system-wide delay and travel time, considering various forms of control and signal priority. MMITSS control was implemented at multiple intersections, and evaluated multiple requests for priority based on a hierarchy of control considerations.

This study evaluated both TSP and FSP applications under various operational conditions. The MMITSS system processes multiple requests for priority, which may be received from connected transit vehicles and connected trucks at any time. The priority request is determined by a hierarchical level of priority. For this simulation study, connected trucks are given a higher priority level than transit vehicles and 1000:1 weight factors were given to trucks and transit vehicles, respectively.

Transit and truck routes were illustrated earlier in Figure 4-10. Trucks utilized the northbound and southbound routes of Gavilan Peak, with no turning movements. Transit vehicles traveled between the eastern and western ends of the study corridor, also with no turning movements. The transit and truck routes analyzed in simulation were the same routes analyzed during field data collection for the same TSP and FSP scenario.

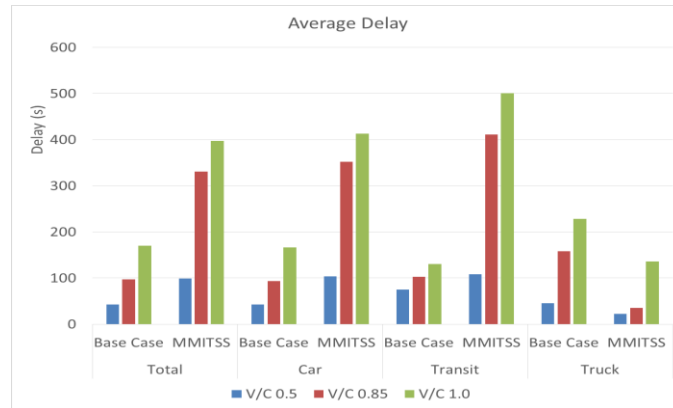
On Daisy Mountain Drive, 2 percent of the eastbound and westbound vehicles were simulated as transit vehicles. The remaining 98 percent were simulated as passenger cars. On Gavilan Peak, 20 percent of the northbound and southbound vehicles were simulated as trucks. All remaining vehicles were simulated as passenger cars. For the MMITSS scenarios, all trucks and transit vehicles were modeled as equipped vehicles. For base case scenarios, all vehicles were modeled as unequipped.

Figure 4-23 presents system-wide impacts for the combination of TSP and FSP applications, under various congestion levels. The combined TSP and FSP applications reduced truck delay by 51.1 percent, 77.9 percent, and 40.4 percent for V/C ratios 0.5, 0.85, and 1.0, respectively. However, significantly increased delays were observed for transit and passenger vehicles when the combined applications were implemented on the Arizona network, as shown in the figure. The increased delays were mostly caused by the increased green time requirements on truck approaches at the Gavilan Peak Intersection. It is also notable that the MMITSS application significantly increased overall system delay (up to 239%) compared with the base case scenario.

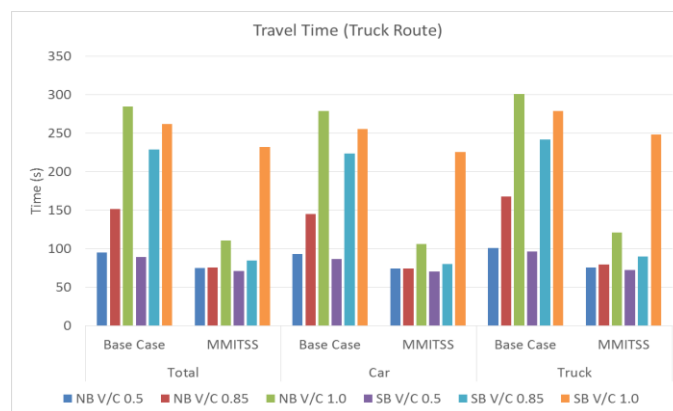
Figure 4-24 compares travel times on truck routes, with and without the MMITSS application. According to the simulation results, all vehicle types on the truck route effectively saved travel time compared with the base case scenarios. In particular, unequipped passenger cars and connected trucks experienced travel time reductions of 64.2 percent and 62.7 percent, respectively, with the MMITSS applications. This indicates that MMITSS was effective in assigning priority to trucks.

Figure 4-25 illustrates radar diagrams for comparing intersection delays with and without the MMITSS TSP and FSP combination application. The figure shows that severe traffic delays were observed on the westbound approach of Gavilan Peak. These delays were triggered by reduced green durations on the westbound approach. Connected trucks on the northbound and southbound approaches of

Gavilan Peak were given a higher priority than transit vehicles. The figure also illustrates that the southbound delay at Dedication was increased from 19.8 to 48.9 s under the MMITSS application. This increased delay was caused by the congestion at Gavilan Peak, which is located nearby. Right-turning vehicles on the southbound approach were partially blocked by westbound approaching vehicles from Gavilan Peak, thus increasing delay of the southbound vehicles.



**Figure 4-23. Delay Comparison of Arizona TSP and FSP Combination Scenarios**



**Figure 4-24. Travel Time Comparison on Truck Routes of Arizona TSP and FSP Combination Scenarios**

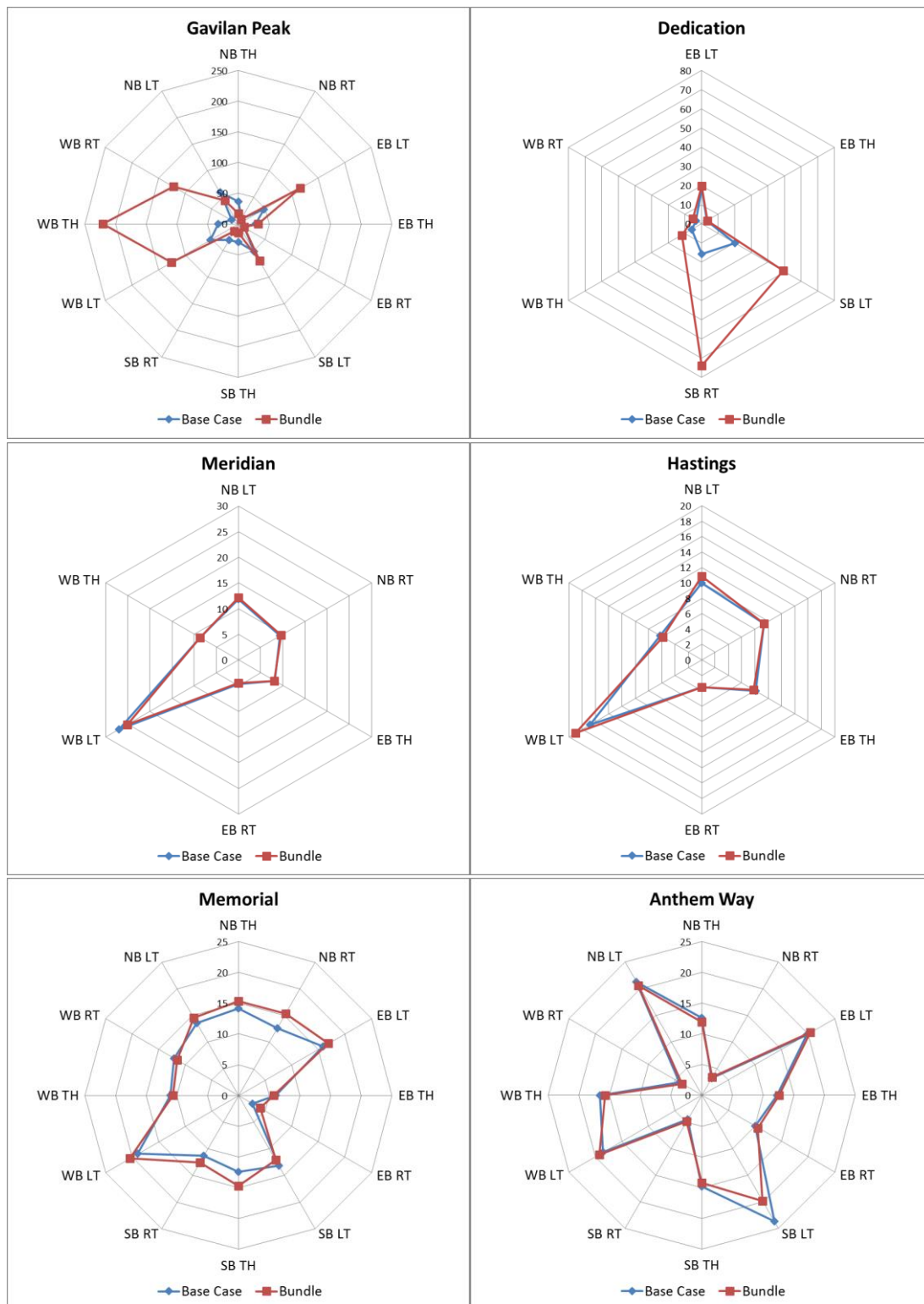
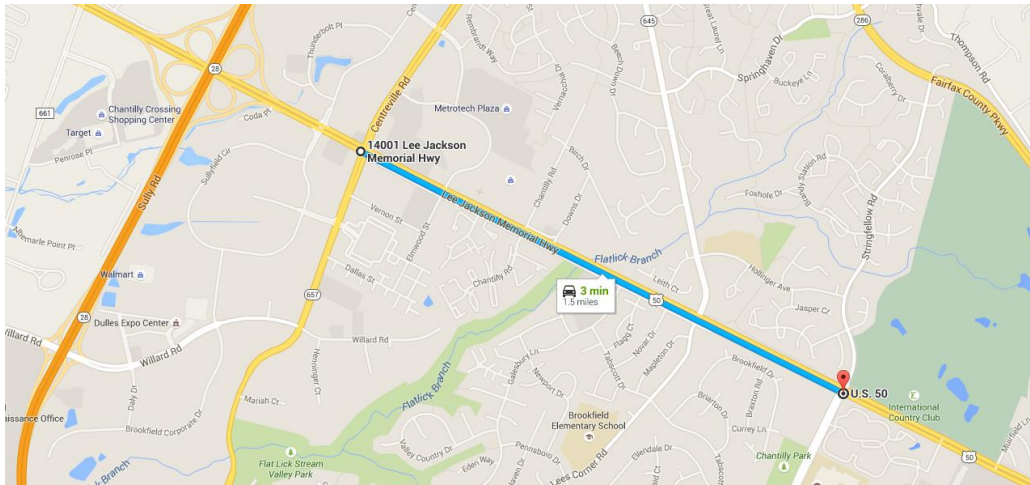


Figure 4-25. Intersection Delay for the Arizona TSP and FSP Combination Scenarios (V/C 0.50)

## 4.4 Virginia Simulation Model

### 4.4.1 Virginia Simulation Model Development

The Virginia simulation analysis was performed for the purpose of assessing MMITSS performance at an independent site. Through extensive simulations of hypothetical scenarios and conditions, and benefiting from lessons learned with the Arizona prototype, the Virginia evaluation allowed site-independent analysis of MMITSS impacts. These results will help to assess the potential impacts of broader MMITSS deployment.



**Figure 4-26. Virginia U.S. 50 Simulation Test Site (Source: Map data ©2015 Google)**

The study section of U.S. Route 50-Chantilly, illustrated in Figure 4-26, is one of the most heavily congested arterials in the northern Virginia area (or Washington, DC, metropolitan area). The corridor, which is typically used as a major commuter route, connects two highly congested highway interchanges on U.S. Route 28 and I-66. Moreover, drivers frequently use this corridor as an alternative to I-66. The study corridor extends over 2.4 km (1.5 mi) and covers six signalized intersections. The study section has three lanes per direction of travel. Some intersections have six lanes per direction, including two left-turn lanes and one right turn lane. The study section starts at Centreville Road to the west and extends eastward to Stringfellow Road.

Traffic volume in the morning peak hour typically reaches 2,700 vehicles/hour in the eastbound direction, and 2,800 vehicles/hour in the westbound direction. Closely spaced signalized intersections in the corridor experience severe congestion during the morning peak period. Of the six signalized intersections, the Centreville and Stringfellow intersections experience significant traffic demands on the side streets.



The study corridor is controlled by actuated signal coordination, with optimized cycle lengths between 210 and 240 s. Most of the cycle time is assigned to U.S. 50. The directional distribution of signal timing varies by time of day.

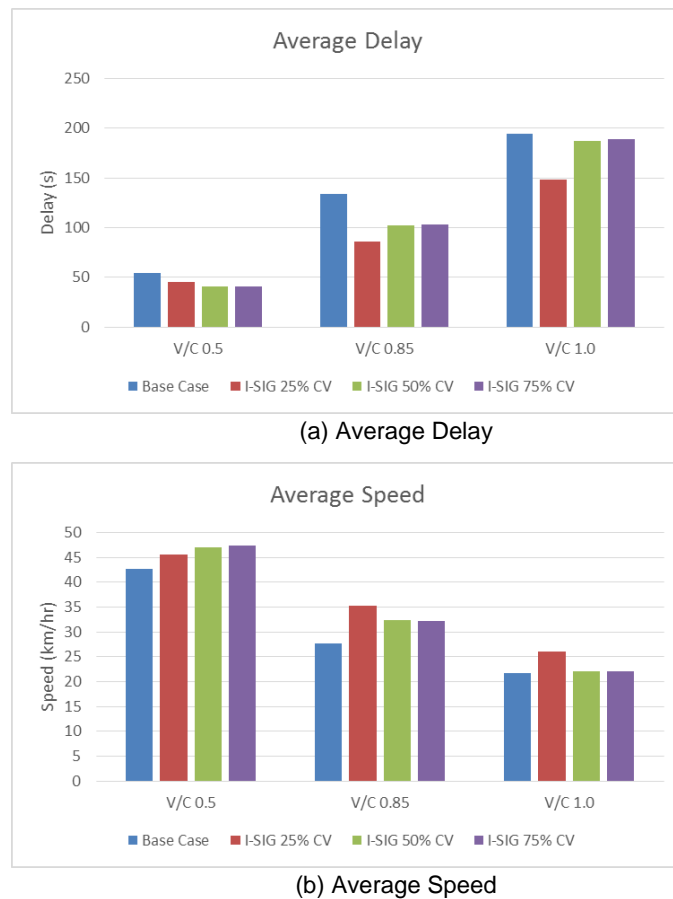
A VISSIM simulation model for the Virginia corridor was developed by the IA team, with technical support from the PD team. The simulation study used turning movement counts, which were provided in the SYNCHRO format by VDOT. The simulation study utilized traffic count data during one hour of the morning peak period. Demands provided by VDOT for the morning peak period were observed to reach a V/C ratio of 0.85, indicating that the test intersections were operating “near capacity.” Two additional simulation scenarios, reflecting V/C ratios of 1.0 and 0.5, were created by proportionally increasing and decreasing traffic demand inputs in the simulation model.

The VISSIM model was calibrated against various forms of traffic data provided by VDOT. The calibrated input parameters included free-flow speeds, saturation flow rates, vehicle speed distributions, and acceleration distributions. Vehicle type characteristics were also adjusted to better match real-world conditions. In particular, the length, width, power distribution, and weight distribution were updated to represent truck dynamics more realistically. Further, the Wiedemann 74 car-following model was adjusted to achieve saturation flow rates of 1,900 vehicles/hour/lane. Each simulation scenario was repeated five times with a different random seed, in order to capture stochastic properties of the VISSIM software. Operational scenarios evaluated during the Virginia simulation study were identical to the scenarios examined during the Arizona simulation study.

#### **4.4.2 Virginia I-SIG Simulation Results**

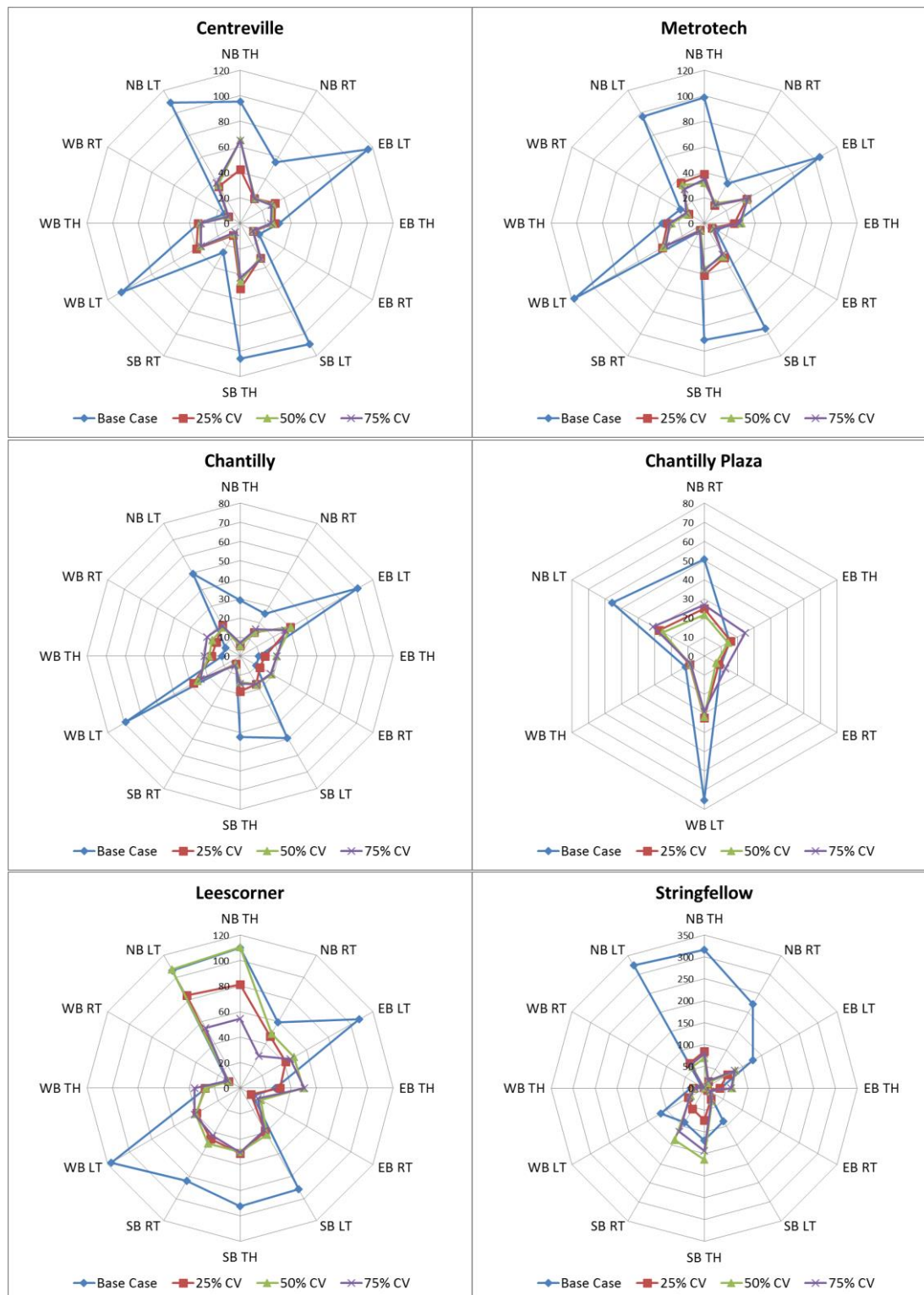
The simulation study investigated system-wide impacts of I-SIG under various congestion levels. Figure 4-27 illustrates the impact of I-SIG operation on system-wide delays and speeds. The implementation of I-SIG significantly reduced vehicle delay and significantly increased average speed. For V/C ratios of 0.5, I-SIG reduced vehicle delays by 16.7 percent, 24.1 percent, and 25.2 percent for CV MPRs of 25 percent, 50 percent, and 75 percent, respectively. This implies that an increased number of CVs in the network would improve system performance. However at V/C ratios of 0.85 and 1.0, the most significant delay reductions (35.5%) were observed at a CV MPR of only 25 percent.

The simulation study also evaluated the impacts on average vehicle speed for different I-SIG scenarios. The study found that I-SIG increased average vehicle speeds by 9.2 percent, 20.2 percent, and 7.7 percent for V/C ratios of 0.5, 0.85, and 1.0, respectively, compared with the actuated control system. In summary, the study found optimum conditions for operating I-SIG at the 0.85 V/C ratio and 25 percent CV MPR. This combination of conditions reduced vehicle delays by an average of 35.5 percent and increased vehicle speeds by an average of 27.1 percent.



**Figure 4-27. Delay and Speed Comparison in the Virginia I-SIG Scenarios**

Figure 4-28 compares the intersection delay for all six intersections. The simulation results demonstrate that I-SIG significantly reduces delays for all intersections compared with the base case. Specifically, the MMITSS system improved delays by up to 47.2 percent and 51.0 percent at the Centreville and Stringfellow intersections, respectively, which are the most congested intersections. The figure also shows that I-SIG effectively reduced side-street delays in addition to major-street delays.

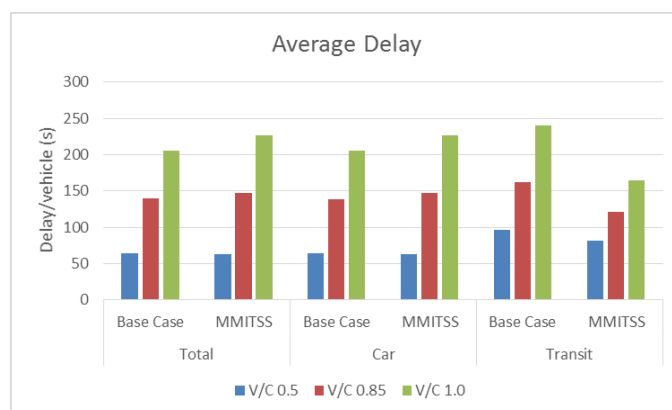


**Figure 4-28. Intersection Delay for the Virginia I-SIG Scenarios (V/C 0.85)**

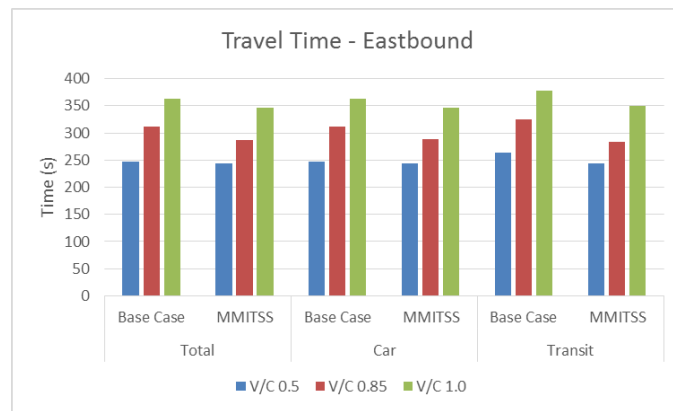
### 4.4.3 Virginia TSP Simulation Results

System-wide impacts of TSP were evaluated at various congestion levels. Similar to the Arizona TSP simulations, 2 percent of eastbound and westbound vehicles were modeled as transit vehicles. Thus, all transit vehicles traveled between the eastern and western ends of the study corridor, with no turning movements. In scenarios of increasing corridor congestion, the number of transit vehicles increased proportionally. Finally, in the TSP scenarios, all transit vehicles were modeled as equipped vehicles, while all other cars were unequipped. By contrast, all vehicles in the base case scenarios were simulated as unequipped vehicles.

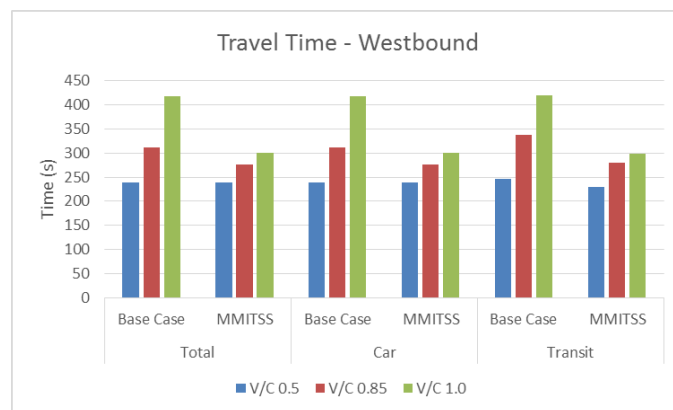
Figure 4-29 compares the average delay of transit vehicles and general traffic, with and without TSP operations, at various traffic demands. Transit vehicles experienced 15.9 percent, 25.6 percent, and 31.5 percent lower delays under TSP for V/C ratios of 0.5, 0.85, and 1.0, respectively. The simulation study also found that for the entire population of vehicles, TSP reduced delays by 1.3 percent at a V/C ratio of 0.5, but increased delays by 10.6 percent at a V/C ratio of 1.0. Figure 4-30 shows the impact of TSP on the average travel times of transit vehicles and passenger cars. Eastbound and westbound trips on U.S. Route 50 were utilized for the analysis. Simulation results demonstrated that TSP reduced travel times for both transit and passenger vehicles. Specifically, the application reduced travel times by 12.8 percent and 28.8 percent for eastbound and westbound transit vehicles, respectively, and reduced travel times by up to 28.1 percent for regular cars. Travel time reductions were most significant at V/C ratios of 0.85 and 1.0. Under these limited simulation scenarios and network conditions, maximum TSP benefits for connected transit vehicles were observed at a V/C ratio of 1.0. The simulations indicate that TSP effectively facilitates the movement of transit vehicles through traffic-signal-controlled intersections. However, the study also found some negative impacts of TSP implementation, in the form of increased system-wide delays on the Virginia network.



**Figure 4-29. Delay Comparison in the Virginia TSP Scenarios**



(a) Travel Time - Eastbound



(b) Travel Time - Westbound

**Figure 4-30. Travel Time Comparison in the Virginia TSP Scenarios**

The individual intersection delays are illustrated in Figure 4-31. These radar diagrams show that TSP reduced delays on transit routes but increased side-street delays for most intersections. In particular, transit and passenger vehicles along transit routes experienced up to 34.7 percent and 32.1 percent delay reductions. However, transit and passenger vehicles on side streets experienced up to 128.4 percent and 59.2 percent delay increases at the Centreville and Stringfellow intersections, respectively, which are the most congested intersections. Figure 4-32 illustrates average queue lengths and vehicle stops at the Centreville intersection for various CV MPR scenarios. The figure clearly demonstrates that TSP generally benefits vehicles on the transit routes but creates longer queue lengths (and more vehicle stops) for vehicles on the side streets.

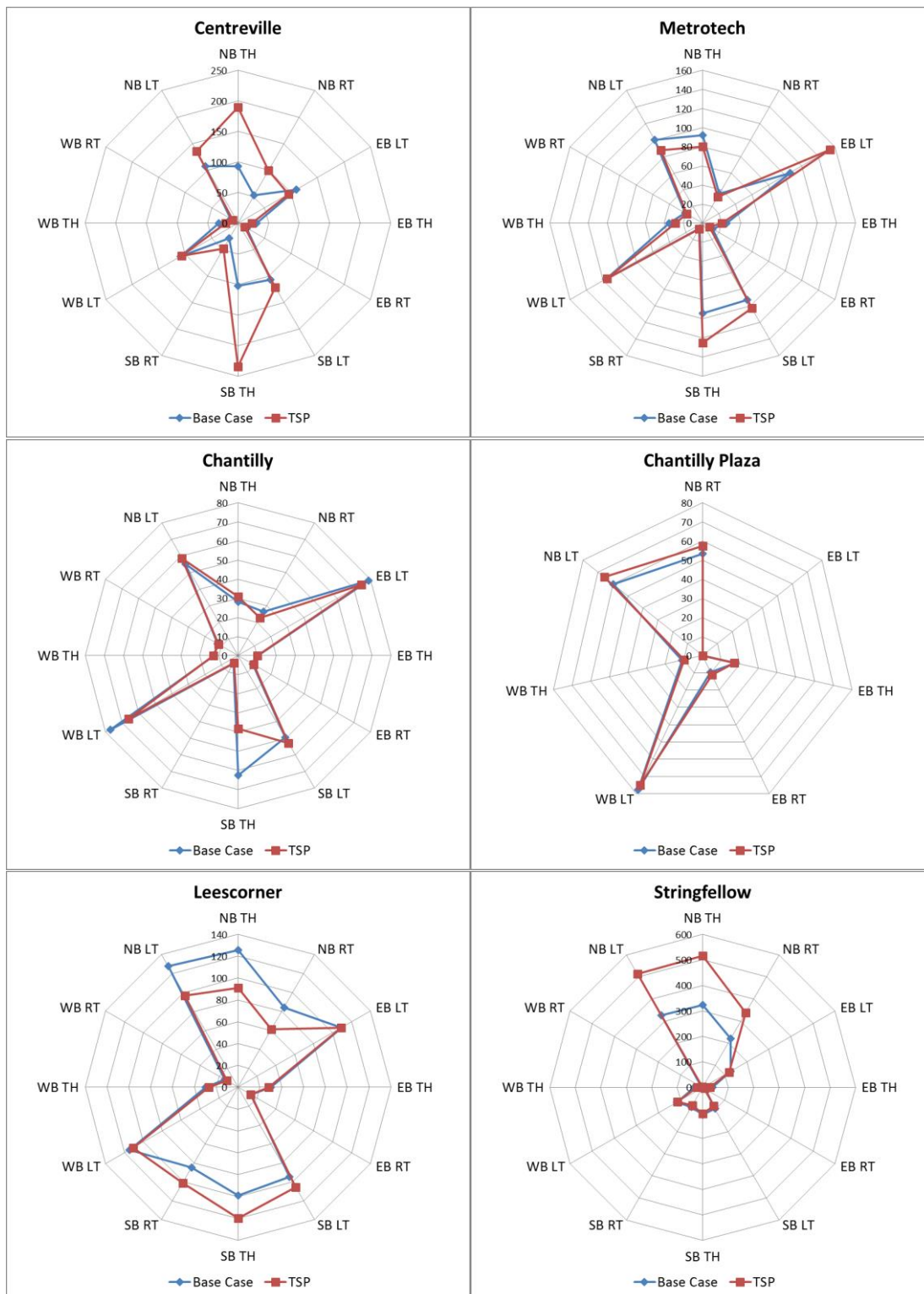
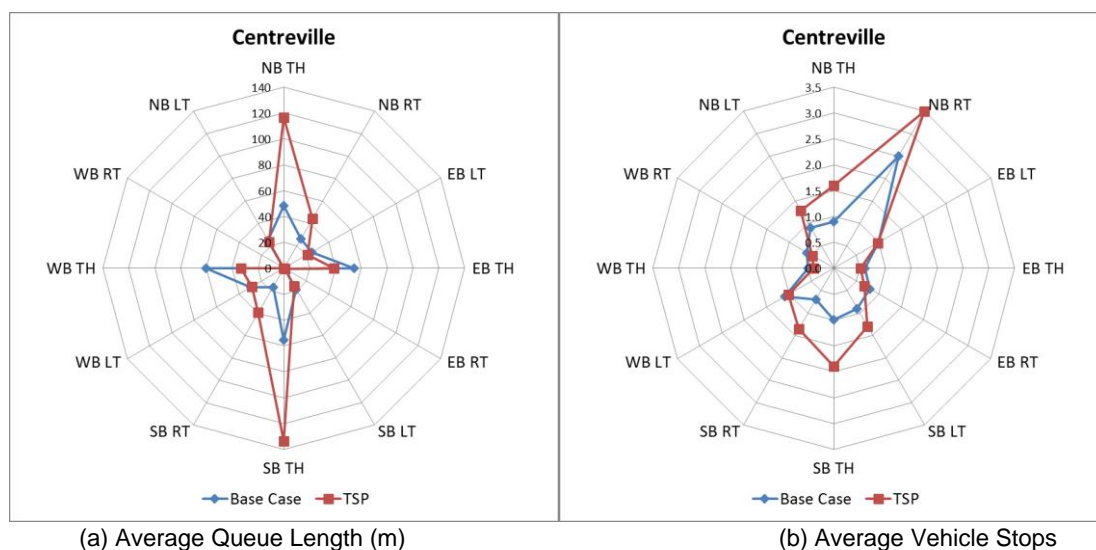


Figure 4-31. Intersection Delay for the Virginia TSP Scenarios (V/C 0.85)



**Figure 4-32. Queue Length and Vehicle Stops in the Virginia TSP Scenarios (V/C 0.85)**

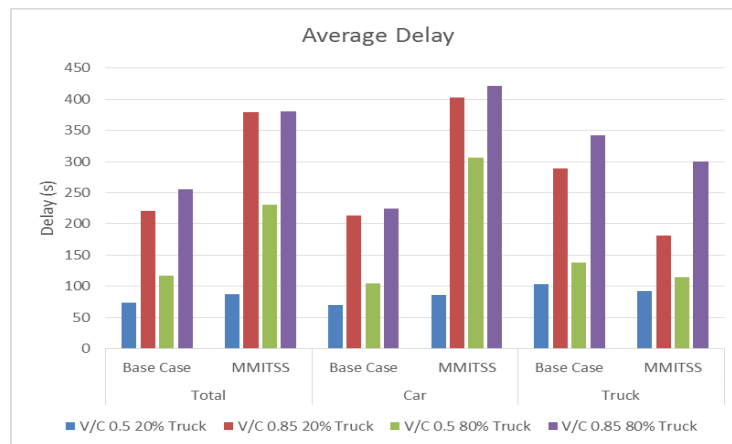
#### 4.4.4 Virginia FSP Simulation Results

This section presents system-wide FSP impacts for two congestion levels, and two truck composition rates. Similar to the Arizona FSP simulation study, this study investigated the combination of V/C ratios of 0.5 and 0.85, and truck composition rates of 20 percent and 80 percent, assuming the test corridor is utilized as a major freight route. All trucks were assumed to be equipped for the FSP scenarios. In the base case scenarios, all trucks were unequipped. Also, trucks were only allowed to travel between the eastern and western ends of the study corridor, with no turning movements.

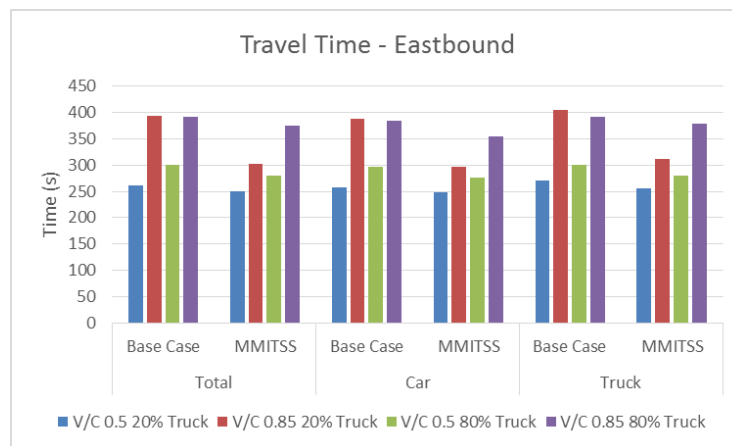
Figure 4-33 illustrates the system-wide delay of freight vehicles and general traffic, with and without FSP, for various operational scenarios. The figure shows that FSP significantly reduced average truck delays. In particular, FSP reduced transit delays by up to 37.2 percent for the 20-percent truck composition scenario. However, FSP significantly increased system-wide delays for the overall population of vehicles by up to 97.4 percent. Finally, FSP produced more efficient traffic operations under the 20-percent connected truck scenario relative to the 80-percent connected truck scenario.

Figure 4-34 displays the travel times of trucks and passenger cars, with and without FSP. The study only evaluated eastbound and westbound corridor trips, which utilized the truck routes. FSP reduced truck travel times by up to 40.0 percent and reduced unequipped passenger car travel times by up to 42.4 percent.

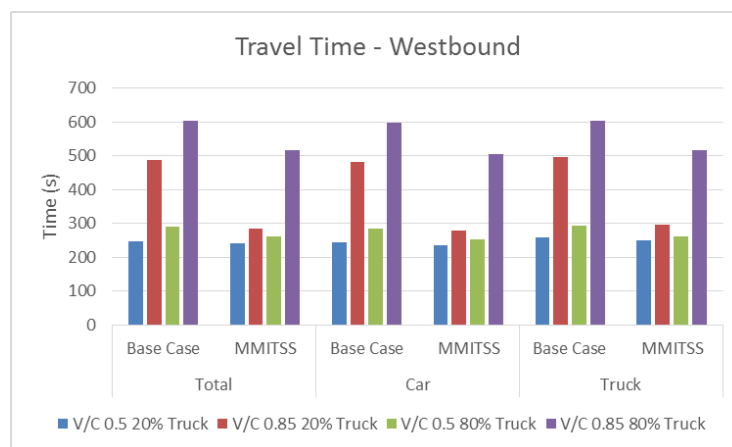
In summary, the simulation study found maximum FSP benefits for trucks at a V/C ratio of 0.85, with a truck MPR of 25 percent. Although FSP significantly reduced the truck delays, system-wide delays were significantly increased, especially in the 80-percent truck composition scenarios.



**Figure 4-33. Delay Comparison in the Virginia FSP Scenarios**



(a) Travel Time - Eastbound

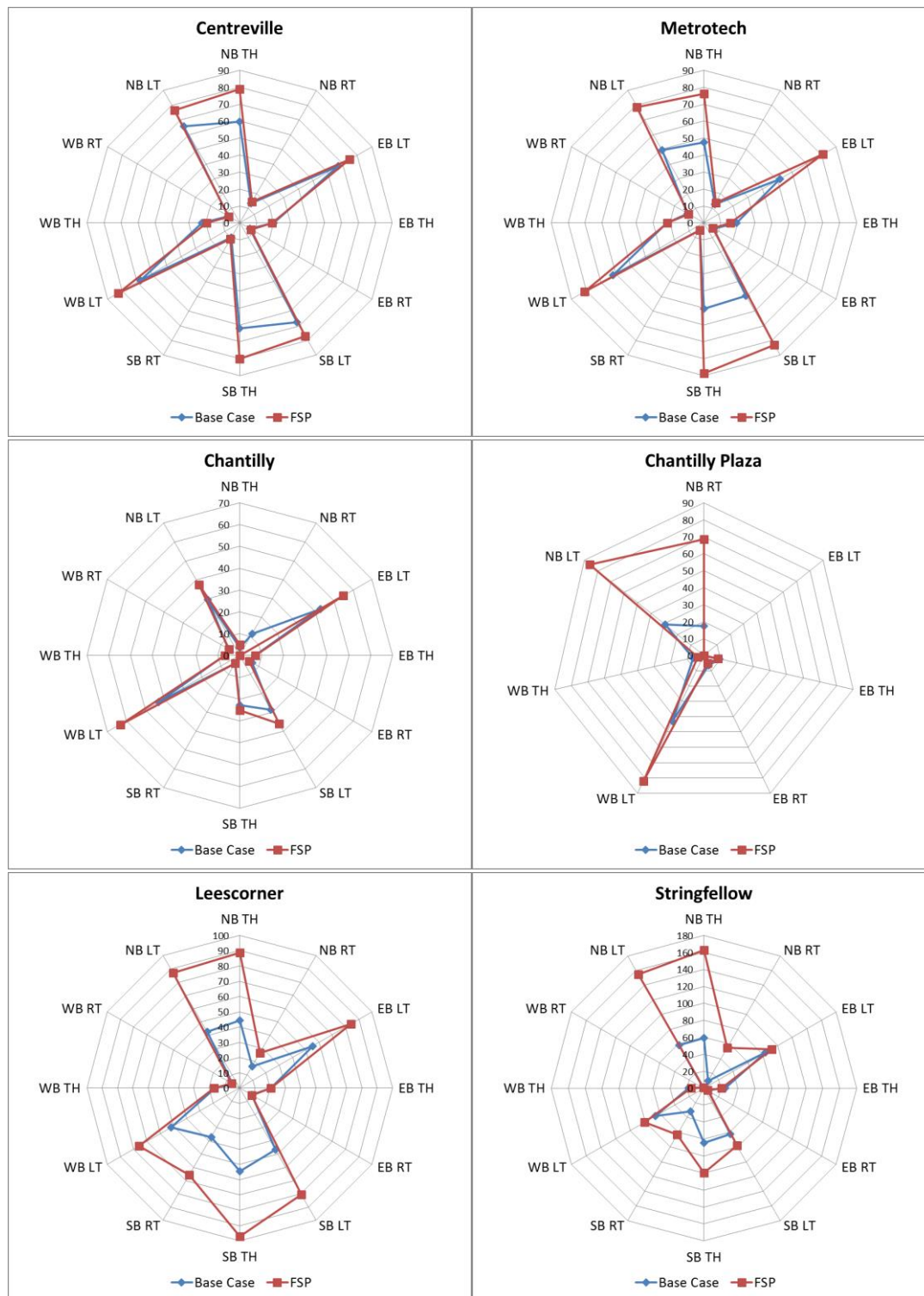


(b) Travel Time - Westbound

**Figure 4-34. Travel Time Comparison in the Virginia FSP Scenarios**



Radar diagrams for comparing individual intersection delays with and without FSP are illustrated in Figure 4-35. The simulation results demonstrate that FSP clearly increased side-street delays at all six intersections but marginally reduced delays for vehicles along truck routes, compared with the base case scenario. The study found that increased side-street delays negatively affected system-wide performance, indicating that the implementation of FSP should be carefully examined by considering network characteristics.



**Figure 4-35. Intersection Delay for the Virginia FSP Scenarios (V/C 0.50, 20% Connected Trucks)**

U.S. Department of Transportation, Office of the Assistant Secretary for Research and Technology  
Intelligent Transportation System Joint Program Office

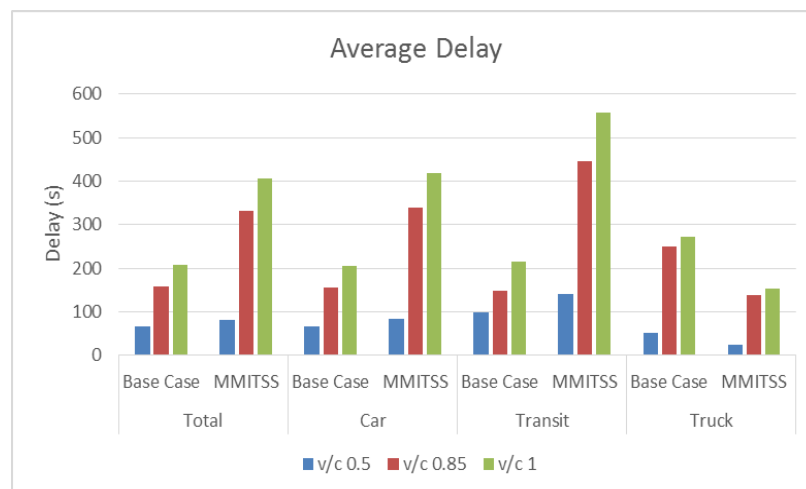
### 4.4.5 Virginia TSP and FSP Combination Simulation Results

One set of simulations was intended to investigate system-wide impacts of the combination of TSP and FSP applications under various congestion levels. Similar to the Arizona simulations, connected trucks were given higher priority than transit vehicles by a weighting factor of 1000:1. Trucks utilized northbound and southbound routes through the Centreville intersection, with no turning movements allowed. Transit vehicles were required to use eastbound and westbound routes of the study corridor, again with no turning movements allowed. Two percent of eastbound and westbound traffic flows were assumed to be transit vehicles, with the remaining 98 percent of vehicles as passenger cars. Twenty percent of the northbound and southbound vehicles were modeled as trucks, with the remaining vehicles as passenger cars. For the MMITSS scenarios, all trucks and transit vehicles were modeled as equipped vehicles. All vehicles were unequipped in the base case scenarios.

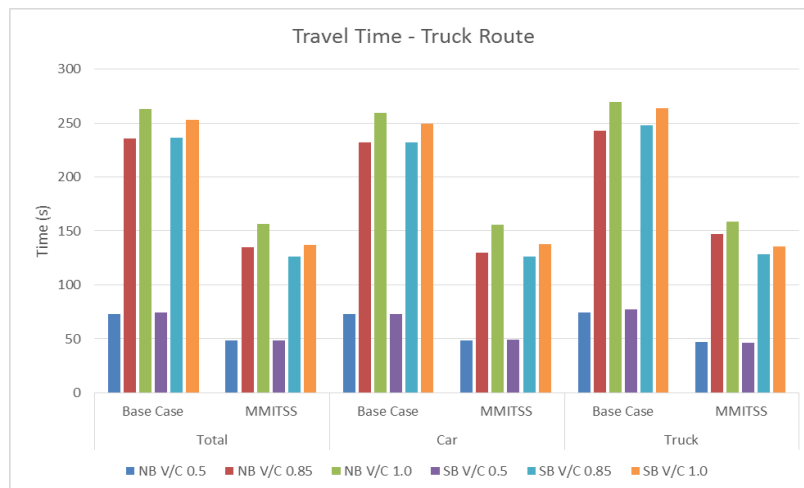
System-wide delays at various congestion levels are illustrated in Figure 4-36. The simulation results demonstrate that MMITSS operations would significantly increase overall network delays. In particular, the combination of TSP and FSP applications would increase network delays by 22.4 percent, 109.2 percent, and 96.4 percent for V/C ratios of 0.5, 0.85, and 1.0, respectively. The increased delays were mostly caused by adjustments in green time due to truck priorities on the truck routes. The figure shows that MMITSS reduced truck delays by 55.2 percent, 44.6 percent, and 44.0 percent for V/C ratios of 0.5, 0.85, and 1.0, respectively. These results are consistent with trucks being given a higher priority than transit vehicles.

Figure 4-37 illustrates travel times for trucks and passenger cars on truck routes, with and without the MMITSS applications. All vehicle types on the truck route experienced reduced travel times. Unequipped passenger cars saw reductions in travel time between 32.6 percent and 45.8 percent. Connected truck travel times decreased by 36.8 percent to 48.6 percent.

In summary, the simulation study found that connected truck mobility was significantly improved by the MMITSS applications, but system-wide delays were significantly increased.



**Figure 4-36. Delay Comparison of Virginia TSP and FSP Combination Scenarios**



**Figure 4-37. Travel Time Comparison on Truck Routes of Virginia TSP and FSP Combination Scenarios**

Figure 4-38 illustrates radar diagrams for visualizing average vehicle delay with and without the MMITSS TSP and FSP combination applications. These results demonstrate that the MMITSS operation successfully executed a hierarchical level of priority. In particular, the MMITSS application provided priority for trucks traveling southbound and northbound at the Centreville intersection, and priority for transit vehicles traveling eastbound and westbound along the study corridor. The application reduced delays on truck routes and transit routes by up to 50.8 percent and 18.3 percent, respectively, at the Centreville intersection.

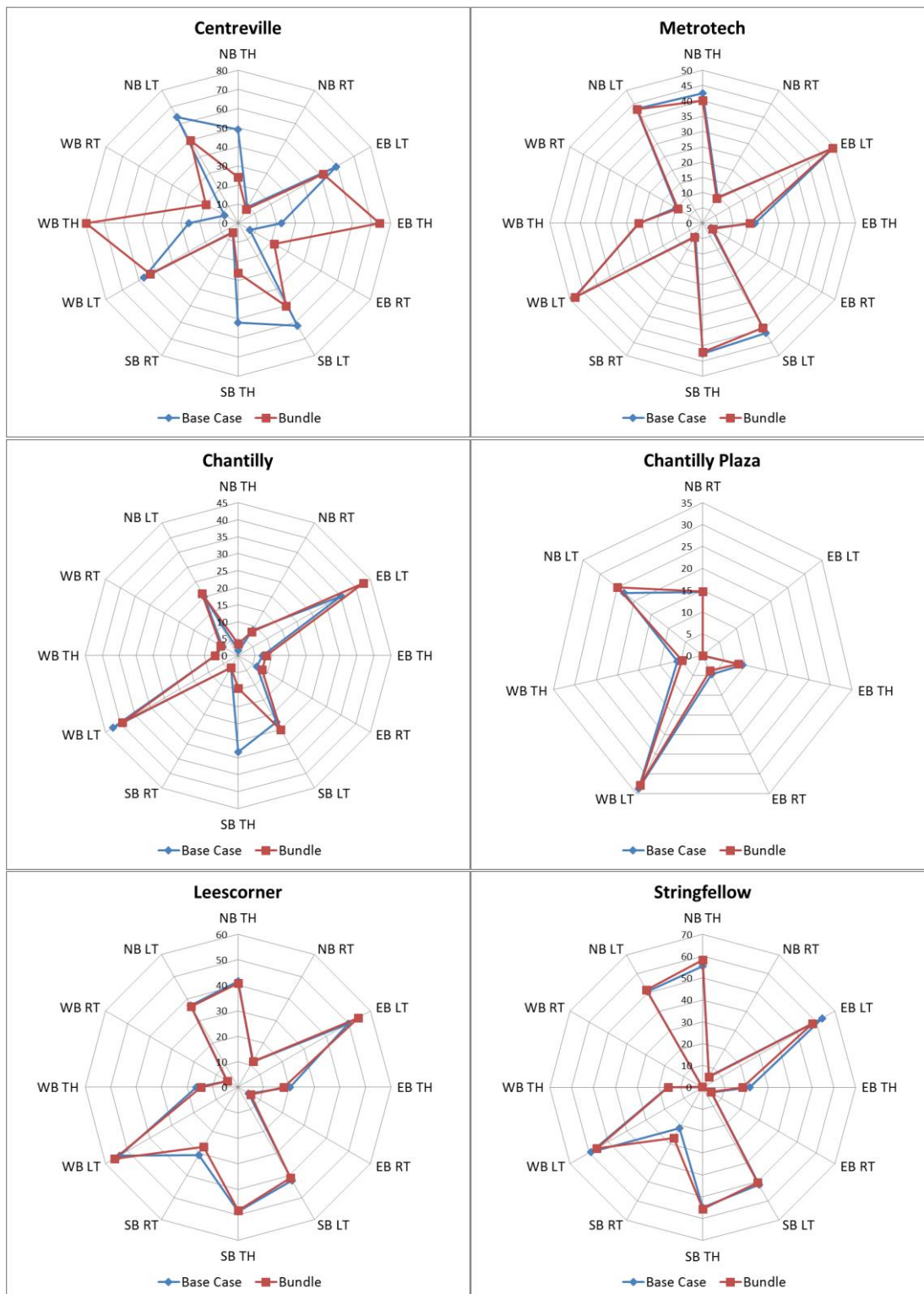


Figure 4-38. Intersection Delay for the Virginia TSP and FSP Combination Scenarios (V/C 0.50)

## 4.5 Comparison of Arizona and Virginia Simulation Results

The simulation study evaluates and demonstrates the impacts of deploying MMITS applications and strategies in a simulation environment under various operational conditions. The simulation effort can be used to evaluate the broader impacts of individual applications, logical combinations applications, and conflicts and synergies for maximum benefit. The objective of the simulation study was to identify the most beneficial operational conditions for each MMITSS scenario. This section summarizes the optimum operational conditions for obtaining system-wide benefits based on the Arizona and Virginia simulation results. Table 9 compares network characteristics for the Arizona and Virginia simulation networks. As shown in the table, Virginia network has a 94 percent higher traffic demand than the Arizona network.

**Table 4-5. Comparison of Arizona and Virginia Simulation Networks**

| Characteristics                                    | Arizona Network                    | Virginia Network                    |
|--|------------------------------------|-------------------------------------|
| Facility type                                      | Arterial                           | Arterial                            |
| Demand at V/C 1.0                                  | 7,149 veh/hr (21% through traffic) | 13,851 veh/hr (47% through traffic) |
| No. of lanes on the study corridor (per direction) | 3 lanes                            | 3 lanes                             |
| Saturation flow rate                               | 1,800 veh/hr/lane                  | 1,900 veh/hr/lane                   |
| No. of traffic signals                             | 6                                  | 6                                   |
| Length of the study corridor                       | 3.04 km (1.9 mile)                 | 2.4 km (1.5 mile)                   |
| Speed limits of the study corridor                 | 64 km/hr (40 mph)                  | 72 km/hr (45 mph)                   |

Table 4-6 through Table 4-9 demonstrate the system-wide impacts of MMITSS applications. Optimum system-wide benefits of I-SIG, in terms of average vehicle delay, were observed at 75 percent CV and V/C 0.85 levels on the Arizona network, and at 25 percent CV and V/C 0.85 levels on the Virginia network, as shown in Table 4-6. For both networks, I-SIG performed best at the V/C 0.85 congestion level. For both networks, performance at the 50-percent and 75-percent CV ratios were almost identical for I-SIG. For the Virginia network at congestion levels of V/C 1 and V/C 0.85, the benefits of I-SIG decreased as the concentration of CVs increased in the network. This may have been due to communication errors because RSEs could not process data from all connected vehicles. Further study is needed to identify the nature and/or magnitude of I-SIG benefit reductions under congested conditions.

**Table 4-6. System-Wide Benefits of I-SIG (Average Vehicle Delay)**

|                     | Arizona I-SIG Simulation Results |            |           | Virginia I-SIG Simulation Results |            |           |
|---------------------|----------------------------------|------------|-----------|-----------------------------------|------------|-----------|
|                     | V/C (0.5)                        | V/C (0.85) | V/C (1.0) | V/C (0.5)                         | V/C (0.85) | V/C (1.0) |
| <b>I-SIG 25% CV</b> | 13.9%                            | 11.5%      | 10.1%     | 16.7%                             | 35.5%      | 23.5%     |
| <b>I-SIG 50% CV</b> | 17.3%                            | 20.0%      | 10.4%     | 24.1%                             | 23.3%      | 3.4%      |
| <b>I-SIG 75% CV</b> | 16.2%                            | 20.6%      | 9.5%      | 25.2%                             | 23.0%      | 2.9%      |

Table 4-7 and Table 4-8 demonstrate the system-wide benefits of TSP and FSP with regard to average travel time. The tables indicate that TSP and FSP effectively improved the mobility of transit vehicles in both traffic network cases. In Table 4-7, TSP did not significantly improve system-wide benefits, and even increased average vehicle delay in some scenarios. Table 4-8 also demonstrates system-wide FSP disbenefits in the Arizona and Virginia networks. The increased FSP delays were caused by truck priority reductions to side-street green times. The tables show that TSP performed better on the Arizona network than on the Virginia network. The exact reason is unknown, but could be related to lower demand levels on the Arizona network. The study found optimum TSP performance for transit vehicles at V/C 0.85 levels for the Arizona network, and at V/C 1.0 levels for the Virginia network. However, the study also found that total vehicle delays were increased up to 10.6 percent and 10.0 percent for the Arizona and Virginia networks, respectively. The most beneficial condition of FSP for trucks was V/C 0.50 at 20-percent connected trucks for the Arizona network, and V/C 0.85 at 20-percent connected trucks for the Virginia network.

**Table 4-7. System-Wide Benefit and Disbenefit of TSP (Average Transit Travel Time)**

|                   | Arizona TSP Simulation Results |         | Virginia TSP Simulation Results |         |
|-------------------|--------------------------------|---------|---------------------------------|---------|
|                   | Total                          | Transit | Total                           | Transit |
| <b>V/C (0.5)</b>  | 0.6%                           | 49.9%   | 1.5%                            | 15.9%   |
| <b>V/C (0.85)</b> | -10.6%                         | 51.4%   | -5.4%                           | 25.6%   |
| <b>V/C (1.0)</b>  | 2.2%                           | 46.4%   | -10.0%                          | 31.5%   |

**Table 4-8. System-Wide Benefit and Disbenefit of FSP (Average Truck Travel Time)**

|                             | Arizona FSP Simulation Results |       | Virginia FSP Simulation Results |       |
|-----------------------------|--------------------------------|-------|---------------------------------|-------|
|                             | Total                          | Truck | Total                           | Truck |
| <b>V/C (0.5) 20% Truck</b>  | -5.0%                          | 53.0% | -18.7%                          | 11.1% |
| <b>V/C (0.85) 20% Truck</b> | -55.6%                         | 51.8% | -72.2%                          | 37.2% |
| <b>V/C (0.5) 80% Truck</b>  | -103.5%                        | 38.6% | -97.4%                          | 17.0% |
| <b>V/C (0.85) 80% Truck</b> | -41.7%                         | 11.4% | -49.2%                          | 12.3% |

Table 4-9 demonstrates the system-wide benefits of the combination of TSP and FSP applications for average travel time. The MMITSS system processed multiple priority requests from both transit and truck vehicles. However, for this simulation study, connected trucks were given a higher priority level than transit vehicles. The simulation study found maximum truck benefits with MMITSS operation at

V/C 0.85 for the Arizona network, and at V/C 0.50 for the Virginia network. However, a different simulation environment having different vehicle compositions and priority weight factors could change these results.

**Table 4-9. System-Wide Benefit and Disbenefit of TSP and FSP Combination Applications (Average Travel Time)**

|            | Arizona TSP/FSP Combination<br>Simulation Results |       | Virginia TSP/FSP Combination<br>Simulation Results |       |
|------------|---|-------|--|-------|
|            | Total   | Truck | Total  | Truck |
| V/C (0.5)  | -130.0%   | 51.1% | -22.4%   | 55.2% |
| V/C (0.85) | -238.8%   | 77.9% | -109.2%  | 44.6% |
| V/C (1.0)  | -133.5%   | 40.4% | -96.4%   | 44.0% |



# Chapter 5 Gaps and Challenges

One goal of this study was to identify gaps and set priorities for future research in the area of MMITSS and related CV research. This section discusses the design issues regarding to the development of the MMITSS simulation model and MMITSS applications that might be helpful in the future study and promotion of MMITSS research.

## 5.1 MMITSS Prototype and Applications Development

The project was planned to analyze real-world prototypes in both Arizona and California. However, due to delays experienced by the California PD team, only the Arizona prototype was evaluated. Field data and simulation analyses were performed for the Arizona prototype site and for an independent site (Virginia test corridor). Some of the applications within the MMITSS scenarios initially planned for testing were not yet ready, including coordinated signal operations, PED-SIG, PREEMPT, and any scenarios that would have required these component applications. Due to this reduction in the scope of work, it is not yet possible to answer all of the original key questions. Instead, the study investigated the impacts of four operational scenarios, namely: I-SIG, TSP, FSP, and the combination of TSP and FSP applications.

## 5.2 MMITSS Simulation Model Limitations

The study found multiple gaps and challenges with the MMITSS simulation model. A SILS system was utilized for the simulation analyses. The MMITSS simulation platform comprised two systems: a Windows platform (which included the VISSIM microscopic traffic simulation software, the BSM distributor program, and the Econolite ASC/3 traffic controller emulator) and a Linux platform (which included an RSE module). Due to the complexity of the simulation components, several limitations were observed during the simulation study:

- Computational limitation with a large number of CVs in a single intersection
  - During the study, it was found that MMITSS applications have difficulty in processing a large number of simultaneous CV actuations. This would translate to communication errors between CVs and an RSE, leading to less efficient traffic operations being observed under higher CV penetration rates.
  - During the MMITSS simulation, when the numbers of CVs are increased in the DSRC communication range of one intersection (e.g., 200 CVs or more in one intersection), the Econolite signal controllers frequently stopped working. Each signal controller was manually monitored to check the status of signal controllers.
- Reduction in lanes (due to lane drops) while traveling along a corridor affected FSP

- The geometric design of the Arizona study corridor caused significant delays on the Arizona network for a V/C ratio of 0.85 and an 80-percent truck composition scenario for eastbound cars and trucks. In the FSP scenarios, trucks were only allowed to travel between the eastern and western ends of the study corridor and were not allowed to make turning movements. However, a reduction in through lanes at the end of the Anthem Way intersection (the last intersection) forced through trucks to change lanes, producing severe congestion at the Anthem Way intersection.
- FSP and TSP have a maximum number of vehicle requests; overload of connected transit and freight vehicles
  - MMITSS TSP and FSP are able to handle at most 10 priority eligible vehicles at a time at an intersection. Under highly congested traffic conditions, there could be more than 10 priority vehicles at the intersection at any time. Whenever any vehicle changes its estimated time of arrival (ETA), the signal timing schedule will be modified, and a new set of NTCIP commands will be sent to the signal controller. It is possible that this will generate more NTCIP commands than the controller can process, hence overflowing the NTCIP message buffer. This buffer overflow can result in the commands aging and not being applied at the desired time. One FSP scenario which is a V/C ratio of 0.85 and an 80-percent truck composition scenario was designed to test the outer limits of the priority requests.
- Speed of real-time simulations
  - The MMITSS simulation was performed in real-time. Due to limitations and constraints of the real-time simulation, each simulation scenario was repeated only five times with different random number seeds. Future studies should increase the number of runs to satisfy statistical significance.

## 5.3 Recommended future research considerations

- Each simulation scenario was repeated only five times with different random number seeds, to address stochastic properties of the simulation model. Future studies should increase the number of runs to satisfy statistical significance.
- Further study is required to identify the impacts of CV density. The simulation study found that computer processing power affected the maximum number of CVs that could be processed in SILS. A sensitivity study is recommended to identify the impacts of CV density in an intersection.
- MMITSS applications cannot identify destinations of CVs in a shared lane. Shared lane impacts should be investigated to improve the performance of side streets.
- The length of right-turn and left-turn pockets affected detection of right-turn and left-turn vehicles. The impacts of turn pocket lengths should be investigated. Research should determine optimal lengths for right-turn and left-turn lanes at MMITSS intersections.
- The current version of MMITSS cannot process a coordinated section of signals. Further research is recommended for coordinated I-SIG application.

- The current version of MMITSS does not support the combination of I-SIG and other priority applications including TSP and FSP. Further research is recommended for the combination of I-SIG and other priority applications.
- The TSP simulation study used a random departure method for transit vehicles. The impact of fixed transit schedules having various transit service frequencies should be investigated.
- For the simulation studies, TSP was compared against a “No Priority” base case. Further study is required to compare MMITSS TSP versus traditional TSP.
- The TSP simulation study did not investigate the impacts of bus stops. Further study on near-side and far-side bus stop impacts is required to better understand the effectiveness of TSP.
- Side-street demands significantly affect system-wide TSP and FSP performance. Further study is required to evaluate the impacts of various side-street demand levels.
- The study investigated FSP impacts under two fixed truck percentages (20% and 80%). The impacts of other truck demand levels should be investigated.
- Fuel consumption and emissions from trucks are frequently used as major MOEs for freight studies. Further study is needed to identify the energy and environmental impacts of FSP.
- For the combination of TSP and FSP applications, further study is needed to evaluate the impacts of various transit and truck demand levels.

# Chapter 6 Summary

## 6.1 Lessons Learned

The following table lists the lessons learned from the MMITSS IA project. These lessons are categorized by topics and finding/issues.

**Table 6-1. Lessons Learned**

| Category                                 | Topic  | Finding/Issues   |
|--|--|--|
| Field study and simulation study results | MMITSS Field Study: I-SIG  | I-SIG operation reduced average delay by up to 13.6% for both equipped and non-equipped cars.  |
|  | MMITSS Simulation Study: I-SIG                                   | Maximum system-wide benefits from I-SIG were observed at V/C 0.85 with 75% CV on the Arizona network, and at V/C 0.85 with 25% CV on the Virginia network. I-SIG reduced average delay by up to 20.6% on the Arizona network and by up to 35.5% on the Virginia network.   |
|  | MMITSS Simulation Study: TSP                                     | Optimum TSP performance for transit vehicles was observed at V/C 0.85 on the Arizona network and at V/C 1.0 on the Virginia network. For equipped transit vehicles, TSP reduced average delay by up to 51.4% on the Arizona network and by up to 31.5% on the Virginia network.                                    |
|  | MMITSS Field Study: FSP  | FSP operation reduced average delay up to 49.0% for equipped trucks and 26% for non-equipped cars.   |
|  | MMITSS Simulation Study: FSP                                     | The most beneficial condition for trucks was V/C 0.50 with 20% connected trucks for the Arizona network, and V/C 0.85 with 20% connected trucks for the Virginia network. For equipped trucks, FSP reduced average delay by up to 53.0% on the Arizona network and by up to 37.2% on the Virginia network.         |
|  | MMITSS Field Study: Combination of TSP and FSP Applications      | The MMITSS system successfully processed multiple priority requests from both transit and truck vehicles. During a limited amount of field data collection, the combination of TSP and FSP applications reduced average delay by up to 10.5% for equipped transit vehicles and by up to 70.8% for equipped trucks. |
|  | MMITSS Simulation Study: Combination of TSP and FSP Applications | The maximum truck benefit under TSP and FSP combination operation was observed at V/C 0.85 for the Arizona network and at V/C 0.50 for the Virginia network. For equipped trucks, MMITSS reduced average delay by up to 77.9% on the Arizona network and by up to 55.2% on the Virginia network.                   |

| Category                     | Topic                          | Finding/Issues   |
|------------------------------|--------------------------------|--|
| Simulation model development | Simulation network development | In the simulation model, links and intersection locations should be exactly matched to a high-resolution map, and carefully calibrated. The simulation model locates vehicles on the roadway based on a lane-based map to compute desired service phases and ETAs for each CV. If the simulation model does not match the map data, MMITSS applications may provide inaccurate traffic signal information. |
|                              | Map data file construction     | A detailed map data file for each intersection should be carefully calibrated. Incorrect map data may place CVs in the wrong lane, such that desired service phases may not be provided.   |
|                              | DSRC communication range setup | DSRC communication ranges should be carefully calibrated based on network characteristics. For example, if a side street has a single shared lane, MMITSS applications cannot identify destinations of approaching vehicles and will assume through destinations for all vehicles. In this case, MMITSS may provide incorrect service phases.  |
| SILS Setup                   | Computer setup                 | Computers used for SILS should be powerful enough to process all CV information without latency. If not, some computers may not be able to process all CV information in the network.  |

## 6.2 Conclusions

The study evaluated the potential impacts of MMITSS applications based on a field implementation and simulation study. The MMITSS simulation model assessed the potential impacts of a broader MMITSS deployment, which will ultimately facilitate the site-independent analysis of MMITSS applications. The study also evaluated the effectiveness of the MMITSS application to identify the most beneficial operational conditions for each MMITSS operational scenario through a combination of simulation variables and traffic demand levels.

The field study demonstrated that FSP effectively reduced the delay of connected trucks and unequipped vehicles compared with the base case operations. MMITSS TSP and FSP combination operations improved the travel times of connected transit vehicles and trucks. Field test results also indicated that I-SIG considerably reduced travel time reliability compared with the base case.

The I-SIG simulation study found that I-SIG effectively achieved vehicle delay reductions and speed increases. The simulation results indicated that TSP reduced travel time for both transit and passenger vehicles on the corridor where TSP was operated but might increase system-wide delay due to reduced green times on the side streets. FSP simulation results indicated that FSP successfully reduced travel times and delays for connected trucks. However, the FSP application also increased system-wide delay due to increased delays on side streets. The simulation study also found that the

combination of TSP and FSP applications was effective in assigning priority to trucks based on a predefined hierarchy of control. In this scenario, connected trucks were given a higher priority level than transit vehicles, but MMITSS can be applied to multiple modes, including emergency vehicles, pedestrians, and special service vehicles at signalized intersections.

While the study demonstrated that the MMITSS system can significantly benefit the system-wide performances for the test facilities, the MMITSS system can be effectively improved through data from existing sensors. I-SIG could benefit from existing detection when the market penetration is low or when traffic volume is low. Current emergency vehicle and TSP sensors provide some level of data that can be used in priority applications. Signal control can benefit significantly using CV data to measure queue length, saturation flow rates, startup lost time, etc. These measures are not available without CV data.

Regarding near-term impacts of the MMITSS system, significant benefits are expected for priority control: PREEMPT, TSP, and FSP in an integrated, multiple vehicle environment. Mobility benefits for disabled pedestrians should be immediately possible through the PED-SIG application. Mid-term impacts could include improved signal control (I-SIG) as market penetration increases. Finally, long-term impacts could include reduced dependence on complex infrastructure-based detection systems (only one RSE required), and the added ability to adjust traffic control policy (priority) based on mode (and movement).

The study concludes that MMITSS I-SIG, TSP, FSP, and the combination of TSP and FSP applications effectively improve vehicle travel time, delay, and travel time reliability for equipped passenger cars, trucks, and transit vehicles on the test facility. However, the system may produce negative network-wide impacts. Also, it should be noted that, because the field test and simulation results were based on a specific set of network conditions at the Arizona Connected Vehicle Test Bed and the Virginia test site, MMITSS applications could produce different results on other networks. Consequently, future research should quantify the potential benefits of MMITSS applications on different networks and operational scenarios.

# References

Ahn, K., H. Rakha and J. Collura (2006). Evaluation of Green Extension Transit Signal Priority Strategies using Portable GPS Receivers. Presented at 85th Annual Meeting of the Transportation Research Board, Washington, D.C.

Rodegerdts, L. A., B. Nevers and B. Robinson (2004). Signalized Intersections: Informational Guide, Kittelson & Associates, Inc. **FHWA-HRT-04-091**.

U.S. Department of Transportation (2015). "Dynamic Mobility Applications (DMA) Program." Retrieved June 25, 2015, from [http://www.its.dot.gov/dma/bundle/mmitss\\_plan.htm](http://www.its.dot.gov/dma/bundle/mmitss_plan.htm).

University of Arizona et al (2012). "MMITSS Final ConOps." Retrieved June 23, 2015, from [http://www.cts.virginia.edu/wp-content/uploads/2014/05/Task2.3.CONOPS\\_6\\_Final\\_Revised.pdf](http://www.cts.virginia.edu/wp-content/uploads/2014/05/Task2.3.CONOPS_6_Final_Revised.pdf).

Yiheng Feng, K. L. H., Shayan Khoshmagham , Mehdi Zamanipour (2015). "A real-time adaptive signal control in a connected vehicle environment." Transportation Research Part C: Emerging Technologies **Volume 55**( June 2015): 460–473.

# Appendix A. List of Acronyms

| Acronym | Definition  |
|---------|---|
| ASC     | Actuated Signal Controller                              |
| BSM     | Basic Safety Messages                                   |
| CA      | California  |
| CV      | Connected Vehicle                                       |
| DMA     | Dynamic Mobility Applications                           |
| DOT     | Department of Transportation                            |
| DSRC    | Dedicated Short Range Communication                     |
| EMS     | Emergency Medical/Management Services                   |
| ETA     | Estimated Time of Arrival                               |
| EV      | Emergency Vehicle                                       |
| EVP     | Emergency Vehicle Preemption                            |
| FHWA    | Federal Highway Administration                          |
| FTA     | Federal Transit Administration                          |
| GPS     | Global Positioning Systems                              |
| I-SIG   | Intelligent Traffic Signal System                       |
| ITS     | Intelligent Transportation System                       |
| LOS     | Level of Service  |
| MMITSS  | Multi-Modal Intelligent Traffic Signal System           |
| MOE     | Measures of Effectiveness                               |
| NTCIP   | National Transportation Communications for ITS Protocol |
| OBE     | On-Board Equipment                                      |
| PATH    | Partners for Advanced Transportation Technology         |
| RSE     | Roadside Equipment                                      |
| SPaT    | Signal Phase and Timing                                 |
| SRM     | Signal Request Message                                  |
| TSC     | Traffic Signal Controller                               |
| TSP     | Transit Signal Priority                                 |
| UA      | University of Arizona                                   |
| USDOT   | United States Department of Transportation              |
| V2I     | Vehicle-to-Infrastructure                               |
| V2V     | Vehicle-to-Vehicle                                      |
| VDOT    | Virginia Department of Transportation                   |
| WAVE    | Wireless Access in Vehicle Environment                  |
| WSA     | WAVE Service Advertisement                              |



# Appendix B. Sample Driver Instructions for Field Data Collection

## ***MMITSS Field Testing - Driver Quick Reference***

Conference Call Information: Dial: 855-462-xxxx, Code: xxxx900

March 4th, Wednesday 9:00 a.m. to 11:00 a.m.

### **Driver ID 1 - Unequipped Passenger Car Driver 1**

#### **Scenario1: Base Case of Freight Signal Priority – Northbound and Southbound**

- Test 1-1: Data collection of NB and SB data on Gavilan Peak Pkwy.
- Staging Area: Southbound on Gavilan Peak Pkwy, 359 meter (1179 ft) from the test intersection.
- The speed limit is 35 mph
- Try to maintain the traffic stream

Driver name:

GPS Device ID:

| Trip id    | Planned Departure | Planned Arrival | Actual Departure | Actual Arrival | Note |
|------------|-------------------|-----------------|------------------|----------------|------|
| T1-1-D1-1  | 9:00 AM           | 9:10 AM         |                  |                |      |
| T1-1-D1-2  | 9:10 AM           | 9:20 AM         |                  |                |      |
| T1-1-D1-3  | 9:20 AM           | 9:30 AM         |                  |                |      |
| T1-1-D1-4  | 9:30 AM           | 9:40 AM         |                  |                |      |
| T1-1-D1-5  | 9:40 AM           | 9:50 AM         |                  |                |      |
| T1-1-D1-6  | 9:50 AM           | 10:00 AM        |                  |                |      |
| T1-1-D1-7  | 10:00 AM          | 10:10 AM        |                  |                |      |
| T1-1-D1-8  | 10:10 AM          | 10:20 AM        |                  |                |      |
| T1-1-D1-9  | 10:20 AM          | 10:30 AM        |                  |                |      |
| T1-1-D1-10 | 10:30 AM          | 10:40 AM        |                  |                |      |

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