Impact Assessment of Incident Scene Work Zone Alerts for Drivers and Workers (INC-ZONE) and Incident Scene Pre-Arrival Staging Guidance for Emergency Responders (RESP-STG)

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16. Abstract

Response, Emergency Staging and Communications, Uniform Management, and Evacuation (R.E.S.C.U.M.E.) is a bundle of applications that targets the improvement of traffic safety and mobility during crashes and other emergencies that affect the highway network. A key R.E.S.C.U.M.E. focus is on traffic incident management and responder safety. Another is emergency communications for evacuation.

The R.E.S.C.U.M.E. bundle includes the following three applications:
1. Incident Scene Pre-Arrival Staging Guidance for Emergency Responders (RESP-STG)
2. Incident Scene Work Zone Alerts for Drivers and Workers (INC-ZONE)
3. Emergency Communications for Evacuation (EVAC).

This document constitutes the Impact Assessment Report for the INC-ZONE and RESP-STG applications. The assessment includes a qualitative evaluation of a prototype of the two applications that were demonstrated in Maryland on November 13, 2014. It further includes a quantitative analysis that estimates the potential impacts of INC-ZONE and RESP-STG on mobility and safety, using the US 101 San Mateo corridor simulation, and an extrapolation of the impacts using incident data from I-495 in Maryland.

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Executive Summary

Response, Emergency Staging and Communications, Uniform Management, and Evacuation (R.E.S.C.U.M.E.) is a bundle of Dynamic Mobility Applications (DMA) that targets the improvement of traffic safety and mobility during crashes and other emergencies that affect the highway network. A key R.E.S.C.U.M.E. focus is on traffic incident management and responder safety. The current R.E.S.C.U.M.E. application bundle employs vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications in addition to mobile communications technologies used by existing emergency responder dispatch systems. Through increased information sharing, improved situational awareness, and enhanced communications capabilities, R.E.S.C.U.M.E. aims to provide critical information and functions to reduce response time, secondary incidents, and traffic congestion during all emergencies, large or small.

This report highlights the procedures and key findings of the impact assessment performed for two of the three applications within R.E.S.C.U.M.E.—namely, Incident Scene Pre-Arrival Staging Guidance for Emergency Responders (RESP-STG) and Incident Scene Work Zone Alerts for Drivers and Workers (INC-ZONE). The assessment included a qualitative evaluation of a prototype of the two applications that were demonstrated in Maryland on November 13, 2014. It also included a quantitative analysis of the potential impacts of INC-ZONE and RESP-STG on mobility and safety, using a simulation of the US 101 San Mateo corridor.

The qualitative assessment of R.E.S.C.U.M.E. is based on interviews conducted with the participants in the November 13, 2014, demonstration of INC-ZONE and RESP-STG in Sykesville, Maryland. Overall, participants had positive reactions to the potential benefits of the demonstrated applications. They believed that, with some improvements to the technology, such as the enhancement of the accuracy of the GPS system, the bundle has the potential to save the lives of (first and second) responders and motorists. The majority of interviewers recognized the potential of the R.E.S.C.U.M.E. applications in reducing total response and clearance time, delays, and secondary incidents, once these applications become widely adopted.

The quantitative analysis examined INC-ZONE and RESP-STG from different perspectives using performance measures under various categories. Network-wide performance measures assessed how the INC-ZONE and RESP-STG applications can affect the network's performance when implemented at different levels of market penetration. Average network-wide delay was reduced by up to 14 percent when INC-ZONE was used along with an increase in average speeds by up to 8 percent. Furthermore, reduction in clearance times due to RESP-STG was used as an input metric to assess how much reduction in network-wide delay and increase in average vehicle speed could be achieved.

Incident zone level measures were also computed to capture the specific impacts of the applications on the incident zone's mobility and safety. INC-ZONE enabled more vehicles to pass through the incident zone over a given time with better speed and lane management. The increase in section throughput was up to 14 percent. In terms of safety, the reduction in sublink speed in the incident zone was up to 14 percent to enhance the emergency personnel safety at the incident location. There were lesser hard brakings in the incident zone with up to 89-percent reduction in maximum deceleration. This was enabled by early warnings about the incident.

In addition, user benefits for different levels of market penetration were analyzed to demonstrate the benefits that an average user can achieve by using the INC-ZONE application. The vehicles with INC-ZONE had up to 40 percent higher average speeds than vehicles without the application. They also left up to 19 percent longer following distance, enhancing safety around the incident by reducing probabilities of secondary collisions.

Highlighting these user benefits could potentially accelerate the adoption of the R.E.S.C.U.M.E. applications, thus leading to higher market penetration rates and achieving system-wide benefits.

Further, RESP-STG can potentially reduce the emergency vehicles' travel time by up to 23 percent and their number of stops by up to 15 percent.

Chapter 1. Introduction and Background

1.1. Introduction

Response, Emergency Staging and Communications, Uniform Management, and Evacuation (R.E.S.C.U.M.E.) is a bundle of applications that targets the improvement of traffic safety and mobility during crashes and other emergencies that affect the highway network. A key R.E.S.C.U.M.E. focus is on traffic incident management and responder safety. The current R.E.S.C.U.M.E. application bundle employs vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications in addition to mobile communications technologies used by existing emergency responder dispatch systems.

Through increased information sharing, improved situational awareness, and enhanced communications capabilities, R.E.S.C.U.M.E. aims to provide critical information and functions to reduce response time, secondary incidents, and traffic congestion during all emergencies, large or small.

The R.E.S.C.U.M.E. bundle includes the following three applications:

1. Incident Scene Pre-Arrival Staging Guidance for Emergency Responders (RESP-STG)
2. Incident Scene Work Zone Alerts for Drivers and Workers (INC-ZONE)
3. The Emergency Communications for Evacuation (EVAC).[1]

This document details the impact assessment of RESP-STG and INC-ZONE. It includes a qualitative assessment of the INC-ZONE and RESP-STG prototype that was demonstrated on November 13, 2014, in Maryland; it further includes a quantitative assessment through modeling and simulation that uses the US 101 (San Mateo) corridor in California. This portion of the assessment specifically addresses the potential impacts of RESP-STG and INC-ZONE on mobility and safety, both at a microscopic scale around incident zones and at an extrapolated regional level.

The first portion of this report provides the qualitative assessment of the applications' prototype demonstrated in Maryland, based on input provided by demonstration participants. The second portion of the report details the quantitative assessment of the applications in a simulation environment. It includes a description of the simulation corridor and its specific infrastructure facilities, in addition to details on the model's calibration and selection of operational conditions. The report further describes the application modeling in a simulation environment as well as the direct and post-processed results of the analysis. Finally, the report includes a regional extrapolation of the R.E.S.C.U.M.E. impacts, using incident data for I-495 in Maryland.

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[1] EVAC is assessed separately, using the New Orleans Evacuation model. It is not part of this Impact Assessment Report and is addressed in a different document.

1.2. Bundle Functionalities

This section provides an overview of the functionalities of INC-ZONE and RESP-STG. [2]

1.2.1. INC-ZONE

The INC-ZONE application is a communication approach that improves the protection of personnel at incident sites from the threat of oncoming vehicles, particularly where those vehicles are being operated outside of recommended speed limits, and improves lane guidance where there have been crashes, incidents, or other events impacting traffic such as stalled vehicles or vehicles pulled over for moving violations. The INC-ZONE application features an in-vehicle messaging system that provides oncoming drivers with merging and speed guidance around an incident. The INC-ZONE application also provides in-vehicle alerts and warnings to oncoming drivers in violation of speed and lane closure restrictions, for the protection of both the drivers and the incident zone personnel. Finally, the INC-ZONE application includes a warning system for on-scene workers when a vehicle approaching or in the incident zone is being operated outside of safe parameters for the conditions.

Although there are similarities between incident zones and construction work zones such as the possible need for lane closures, the two types of zones are fundamentally different in nature. Specifically, a construction work zone is typically pre-planned and usually involves only a single agency (or at most a few agencies), while an incident zone is unplanned and frequently involves inter-agency responses. Incident zones are the focus of INC-ZONE.

Persons found in an incident zone could include crash victims, law enforcement, emergency medical services (EMS), fire and rescue, HAZMAT response, towing and recovery, and roadway and infrastructure repair workers.

1.2.1.1   Threat Determination

The Oncoming Vehicle Application Component uses inputs such as incident location, speed limit of the incident zone, incident intensity (defined by the number of closed lanes, length of closure area, and criticality of the incident location such as major ramps), and width of incident zone (number of lanes involved) to determine the message that should be issued to the driver and when. This determination is based on the oncoming vehicle speed and location relative to the incident zone, responder vehicles within the incident zone, and the safety zone or buffer zone around and prior to the incident zone where reduced speeds and lane closures apply. The relative locations or distances prior to the incident zone and safety zone are primarily based on guidance and standards within the Manual of Uniform Traffic Control Devices (MUTCD), as well as the content of the messages. Although used for roadside signage, this guidance is applicable for determining advanced placement distances for issuing messages to oncoming drivers and includes consideration of deceleration rates, perception-reaction time, speeds, incident zone buffer space, and visibility distances.

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[2] Functionalities are extracted from the *R.E.S.C.U.M.E. Prototype System Design Document, Final Report*; Battelle; April 11, 2014.

1.2.1.2   Oncoming Vehicle Alerts and Warnings

The INC-ZONE application issues various in-vehicle messages to the driver of an oncoming vehicle via the driver-vehicle interface (DVI), as shown in Figure 1-1. The application issues advisories and alerts to notify drivers in time for them to slow to the advisory or posted speed prior to the safety zone, and advisories and warnings to maintain a speed at or below that advisory or posted speed within the safety zone. The application also issues vehicle-specific, in-vehicle advisory, alert, and warning messages of upcoming shoulder or lane closures within the incident zone. Messages regarding the need for oncoming vehicles to reduce speed and change lanes will be displayed simultaneously. If the oncoming vehicle continues to approach the incident zone in a closed lane, an imminent collision warning is issued based on proximity to the "nearest" responder vehicle within the incident zone.
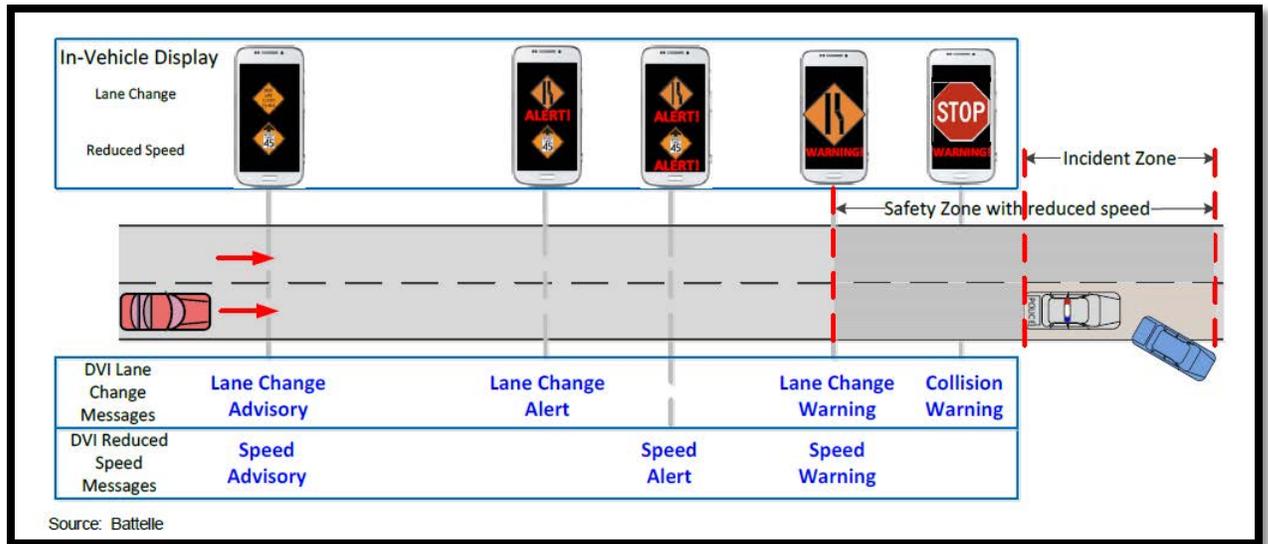
Source: Battelle

Figure 1-1. Prototype Representation of INC-ZONE

1.2.1.3   Responder Alerts and Warnings

The INC-ZONE application issues a series of escalating threat messages to on-scene workers in the incident zone regarding risks posed by oncoming vehicle speed or lane violations, as illustrated in Figure 1-2. Oncoming vehicles send messages via dedicated short-range communications (DSRC) to the responder vehicle regarding their threat level, thereby triggering the issuance of an appropriate message from the responder vehicle to the on-scene responders' personal alert safety system. The escalating threat message set is based on when oncoming vehicles are approaching a speed or lane violation, violating established speed or lane closures within the established safety zone, and posing a collision-imminent direct threat.
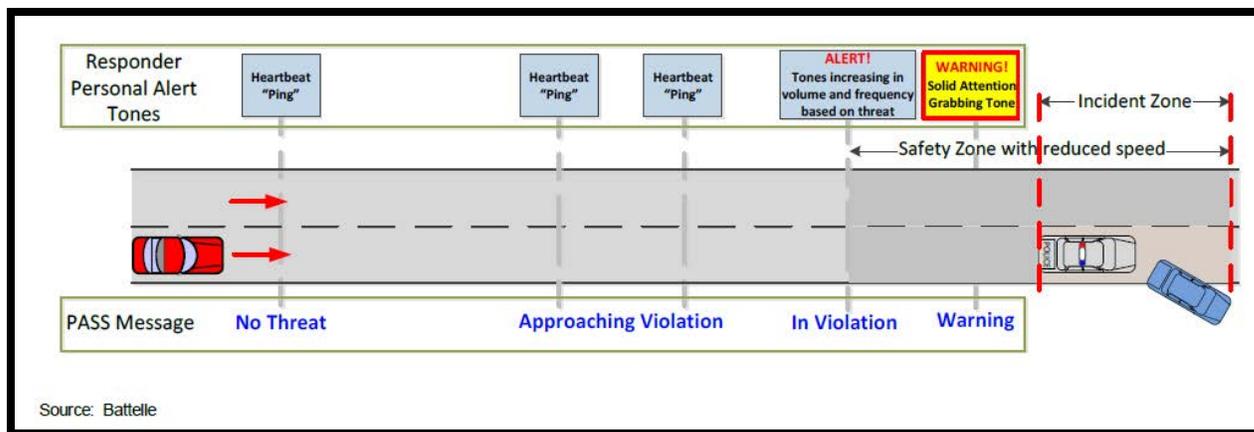
Source: Battelle

Figure 1-2. Prototype Representation of INC-ZONE Responder Alerts and Warnings

1.2.2. RESP-STG

The RESP-STG application provides situational awareness to and coordination among emergency responders—upon dispatch and while en route—to establish incident scene work zones both upon initial arrival and staging of assets, and afterward, if circumstances require additional dispatch and staging. It provides valuable input to responder and dispatcher decisions and actions. A range of data will be provided through mobile devices and other types of communication to help support emergency responder vehicle routing, staging, and secondary dispatch decision-making.

Improving situational awareness to public safety responders while they are en route can help establish incident scene work zones that are safe for responders, travelers, and crash victims while being less disruptive to traffic. Situational awareness information can also provide valuable input to responder and dispatcher decisions and actions.

The RESP-STG application is a collection of integrated functions designed to minimize the adverse effects on mobility and safety caused by an incident affecting the roadways. This is achieved by increasing the preparedness and situational awareness of the emergency responders upon dispatch and while en route to an incident scene. Awareness of this information in advance enables critical, time-saving, and potentially life-saving decisions to be made prior to arrival on scene. These decisions in turn enable the responders to clear the incidents sooner and to enhance the incident staging to facilitate mobility.

1.2.2.1 Vehicle and Equipment Staging

The Vehicle and Equipment Staging function supplies the en-route responders with additional information they can use to determine prior to their arrival on scene where to stage personnel and equipment. This function is responsible for accessing a database of still photographs, satellite imagery, GIS overlays, video feeds, and modeling programs (e.g., predicted HAZMAT plumes) to provide a visual representation of the scene to facilitate the staging of equipment. Additional components such as current traffic conditions and existing vehicles already on scene are also critical

components integrated into the situational awareness picture developed and provided by the Vehicle and Equipment Staging function.

This function receives information from a variety of sources, routed through the Communications function, and uses that information together with on-board databases and Internet-accessible sources to develop a multi-layered spatial representation of the incident. The arriving responder's approach and likely staging will be projected onto the incident as an additional layer.

1.2.2.2 Emergency Responder Status Reporting

This function continuously monitors the location of the en-route responder vehicles as well as the vehicles already on scene (via the INC-ZONE and/or Information Broker). The function develops and maintains the current position of the responder's vehicles. Other information such as traffic encountered, speed, heading, and route to destination are also captured and processed by this function. The function does not report the type of vehicle (e.g., fire truck or tow truck). This information is forwarded to the INC-ZONE and Information Broker via the Communications function.

1.3. Modeling Constraints

While the descriptions of the applications, as detailed in the system design document, can be implemented in real-world scenarios, with some investment in technology and infrastructure, some of these functionalities cannot be modeled within a simulation environment. For the most part, traffic simulation software considers the individual vehicle's behavior and not individual people—travelers, responders, police officers, or workers. Therefore, for the modeling and simulation-based impact assessment, individual vehicle behavior is used and modified to replicate most of the application functionalities, rather than individual personal behavior. For example, the INC-ZONE application includes a functionality that will create audible threat alerts about an errant vehicle for the safety of personnel on scene. Such functionalities cannot be modeled. Additionally, warnings and alerts to drivers to change lanes or slow down are issued as a vehicle command to achieve a desired lane and speed, and based on the built-in functions for compliance rates, the vehicles choose to accept or decline this command. Chapter 3 provides further details about the modeled functionalities.

Chapter 2. Assessment of the Prototype

2.1. Prototype Overview

As part of the R.E.S.C.U.M.E. bundle, INC-ZONE and RESP-STG prototypes were designed, developed, tested, and demonstrated. Battelle and the University of Maryland's Center for Advanced Transportation Technology (CATT) conducted a small-scale demonstration of the two prototypes on November 13, 2014. The qualitative data collection effort was designed to support the impact assessment of the prototypes and the potential future deployment opportunities for the two applications. The main purpose of this demonstration was to test the ability of the applications to provide warning to oncoming vehicles as well as the level of information sent to communication centers and responding officers.

The INC-ZONE prototype is an in-vehicle messaging system that provides drivers with merging and speed guidance as they approach an incident zone. The system sends warning messages to drivers if they are arriving at the incident location at an unsafe speed or trajectory, as well as warning messages to on-scene workers.

The RESP-STG prototype is designed to provide information about the incident scene to emergency responders before their arrival. This information is provided through enhanced public safety communication systems using the existing infrastructure. Emergency responders use the information to make decisions on vehicle routing, staging, and secondary emergency dispatches. The RESP-STG application is integrated into the Capital Wireless Integrated Network (CapWIN) platform and has the following capabilities:

- Automatic vehicle location (AVL) broadcasting and receipt from CapWIN mobile client
- User-controlled "on scene" broadcasting option for first responders at the incident scene and en route to scene
- New mapping engine and mapping data
- New Freeway Incident Traffic Management plan layer
- Enhanced user control of GIS layers.

2.2. Demonstration Overview

The system prototype was developed and tested first in Columbus, Ohio, on June 17, 2014. After additional research and system development, the prototype was demonstrated at the Maryland Police and Correctional Training Commission's Driver Training Facility in Sykesville, Maryland, on November 13, 2014. These prototypes were followed up with a small-scale trial implementation of RESP-STG that began on March 20, 2015, in which six participants from the Maryland State Highway Administration (SHA) started using the enhanced CapWIN system over a period of two to three months. The objective is to increase the participation rate in this effort in Summer 2015, based on the initial experience with those six participants.

Figure 2-1 shows an overview of the test track at which the November 13, 2014, demonstration took place.
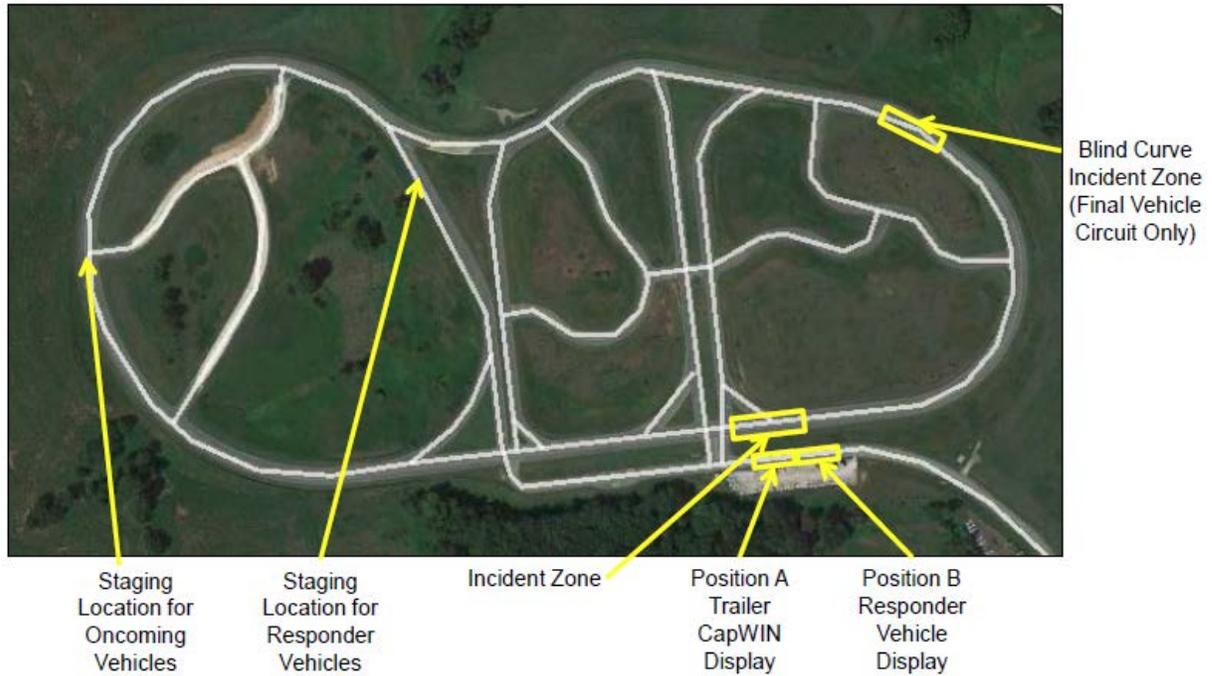
Source: Battelle

Figure 2-1. Overview of the R.E.S.C.U.M.E. Demonstration Test Track in Sykesville, MD

The figure indicates the location of oncoming traffic and responder vehicles as well as the incident zones. Position A Trailer with the CapWIN Display provided location and weather information, and Position B was the location of the Responder Vehicle Display.

During the November 13, 2014, demonstration, 12 scenarios were tested to show the functionality of the RESP-STG and INC-ZONE applications. These applications were viewed from three different perspectives—CapWIN perspective (Position A), responder perspective, and prototype oncoming vehicle perspective.

CapWIN represents a platform in which the RESP-STG application is integrated. Using enhanced AVL features and new mapping engines, CapWIN is designed to improve the ability of first responders to manage response staging and provide better information on the location of other responders from different agencies and disciplines around the incident scene. The demonstration was displayed on the CapWIN platform as first responders arrived at the incident scene, and the responses were monitored.

One of the challenges of this demonstration was placing the connected vehicle applications on the responder and oncoming vehicles. Implementing DSRC messaging between responder and oncoming vehicles to support threat and imminent crash warnings also presented issues. Another challenge and potential improvement area was the implementation of lane-level mapping and an accurate GPS positioning system.

There are plans to conduct a range of integration activities to overcome these challenges. For example, there are plans to develop integrated DSRC, cellular, and Bluetooth communication systems in both oncoming and responder vehicles. The RESP-STG and INC-ZONE applications will be compatible and incorporated into existing responder portable laptops and existing consumer smart phones while using the existing public safety communications equipment.

2.3. Demonstration Participants

Table 2-1 lists the agencies that participated in the November 13, 2014, R.E.S.C.U.M.E. demonstration.

Table 2-1. R.E.S.C.U.M.E. Maryland Demonstration Participants

Type	Stakeholder
Federal Agencies	Intelligent Transportation System Joint Program Office (ITS JPO)
	Federal Highway Administration (FHWA)
	National Highway Traffic Safety Administration (NHTSA)
	Federal Motor Carrier Safety Administration (FMCSA)
State and Local Agencies	Maryland State Highway Administration (MDSHA)
	Maryland State Police (MSP)
	University of Maryland CATT / CapWIN
	Maryland Emergency Management Agency (MEMA)
	Sykesville – Freedom District Fire Department
Other Organizations	Transportation Research Board - Standing Committee on Traffic Law Enforcement (ANB40)
	Transportation Safety Advancement Group (TSAG)
	International Association of Chiefs of Police (IACP)
	Intelligent Transportation Society of America (ITSA)
	National Sheriff's Association (NSA)
Local Public Safety Agencies	Erie County New York Sheriff's Office

2.4. Feedback from Demonstration Participants

Interviews were conducted with participants in the Maryland demonstration to capture their assessment of the demonstrated INC-ZONE and RESP-STG applications. Their responses are summarized below.

Overall, participants were very impressed with the effectiveness of the R.E.S.C.U.M.E. system and believed that the technology "*has the potential to save the lives of [first and second] responders and motorists.*" The following are the main themes and trends that were captured through the interviews.

2.4.1. R.E.S.C.U.M.E. Functionality

Allowing first responders and their managers to have better situational awareness upon arrival at an incident.

The majority of participants believed that once the accuracy of the GPS system improves, the technology can provide situational awareness to not only the first responders but also the second emergency dispatch responders. By having advance accurate information about the incident scene, the emergency response agencies will be able to deploy additional resources as needed.

Enabling responders to arrive and depart the scene of the incident and arrive at their destination quicker and safer

Accurate information on the location of the incident and the initial responding unit could result in more efficient dispatch of other responders. However, the effect of the technology on quicker departures from the incident scene or the earlier arrival of the responders to their destination was not clear to the participants based on this demonstration.

2.4.2. Transformative Benefits

Further refinements are suggested by the participants to fully capture the true benefits and effects of the R.E.S.C.U.M.E. bundle.

Perceived benefits in reducing the total response and clearance times

Participants believed that this technology will result in reduced response and clearance times. Accurate communication between responder agencies and better situational awareness could help avoid responder redundancies and improve the overall clearance procedure.

Perceived benefits in reducing congestion as measured by throughput and delay times

According to some of the participants, advance warnings may reduce some congestion by eliminating surprise slowdowns for approaching vehicles that may cause fender benders. Also, participants believed that if motorists know which lane is closed, they can move into open lanes ahead of time, thus reducing speed variance, which has safety as well as mobility benefits. Also, improved responder safety, reduced secondary crashes, and reduced response and clearance time will have mobility benefits.

Perceived benefits in improving en-route travel times for response vehicles

Participants believed that there may be potential improvements to the en-route travel times once this technology is deployed. Quicker response and clearance times as well as the early warning of the incident through V2V in-vehicle information could also improve en-route travel times and related reliability. Nevertheless, further testing and evaluation would be needed to quantify the benefits of the technology in this area.

Perceived benefits in reducing secondary incidents (with a focus on responder injuries)

Participants generally agree on the potential benefits of the R.E.S.C.U.M.E. technology with regards to reducing secondary injuries. Some of the participants emphasized that this is the area where the

technology has the greatest benefit, as the early warning to approaching motorists seems to have the highest value for deployment.

2.4.3. Wider Deployment

Likelihood that agencies would implement R.E.S.C.U.M.E. applications and integrate them with existing systems

Most participants think that agencies will be receptive to the use of these applications, especially the enforcement and emergency response agencies. As the R.E.S.C.U.M.E. applications become more widely adopted, it will be easier to integrate them with the existing systems. However, participants question potential technical integration issues with the implementation of this system and the costs associated with it.

Barriers for wider implementation of R.E.S.C.U.M.E.

Some of the major barriers for wider implementation of this technology according to the demonstration participants include:

- Cost, legislative, and regulatory requirements to the original equipment manufacturers (i.e., FMVSS[3] and other standards for vehicles), interfaces with INRIX[4] and CATT information technologies, availability of universal GPS data
- Showing consistent, accurate, repeatable information exchange and warnings
- Well-documented benefits of various scenarios, ease of integration into existing systems, system reliability, and number of vehicles equipped with equipment to make these applications work. Since market penetration of onboard equipment (OBEs) in private vehicles will be low for years to come, agencies are considering the implementation of INC-ZONE functionalities with radar technology.

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[3] **Federal Motor Vehicle Safety Standards (FMVSS):** The FMVSS are regulations issued by NHTSA that set minimum safety performance requirements for motor vehicles and certain equipment. The FMVSS establish **performance** requirements without dictating **design** specifications.
[4] http://www.inrix.com/inrix-traffic-app/

Chapter 3. Modeling Assessment Approach

This chapter describes the INC-ZONE and RESP-STG modeling assessment approach and provides details on the modeling analysis scenarios. It also provides an overview of the performance measures used to assess the impacts of the modeled functionalities.

3.1. Baseline Model

The corridor used to assess RESP-STG and INC-ZONE is an 8.5-mile stretch of the US 101 freeway in San Mateo County in California, located approximately 10 miles south of the San Francisco International Airport (SFO) and stretching from Third Avenue in San Mateo to Woodside Road in Redwood City (see Figure 3-1). US 101 is an 8-lane freeway, transitioning to six mixed-flow lanes and two peak-period, two or more occupant (two-plus)high-occupancy vehicle (HOV) lanes south of Whipple Avenue. The HOV lanes are continuously accessible from the mixed-flow lanes, and limited to two-plus HOV during the morning and evening peak hours and open to all vehicles outside those hours. For the northbound (NB) direction, the HOV lane restriction is in effect from 5:00 am to 10:00 am and 3:00 pm to 7:00 pm on weekdays. For the southbound (SB) direction, the HOV lane restriction is in effect from 5:00 am to 9:00 am and 3:00 pm to 7:00 pm on weekdays. The US 101 freeway carries between 200,000 and 250,000 average annual daily traffic (AADT), of which 15 to 25 percent are two-plus HOV vehicles.

The baseline model used 2012 data for calibration and further analysis. All of the features such as HOV and ramp metering were used in the calibrated model so that it is closest to the real network. Table 3-1 summarizes the model features.

Table 3-1. US 101 Study Corridor Details

Name of Corridor	Corridor Type, Length, and Details	Features for Assessing Impacts of INC-ZONE and RESP-STG	Corresponding Calibrated Simulation Model
US 101 (San Mateo)	Freeway segment 8.5 miles long 7 interchanges HOV, Ramp metering during peak hours	Urban freeway with available incident data. VISSIM application programming interface (API) used for re-creating incidents using dynamic setting of link and vehicle attributes. Reusable APIs for INC-ZONE and RESP-STG will be coded to ensure easier transitions between networks.	2012 travel time data used for calibration. Demand data extracted from Caltrans Performance Measurement System (PeMS) database. Incident data used from California Highway Patrol Dispatch Data to create incidents at the locations that historically had highest incident rate.

In terms of the calibration data, data related to special events, adverse weather conditions, work zones, and incidents is available and was used to derive a specific set of operational conditions. Special events that affect the corridor occur in Candlestick Park in San Francisco, about 16 miles north of the northern edge of the study corridor. Candlestick has a seating capacity of slightly over 70,200 people, which is reached about 10 times a year in the fall season during NFL games at the park. Adverse weather conditions are comparatively infrequent and mild compared to other parts of the country. In 2012, there were 26 rain days (with more than trace amounts of rain) out of 251 non-holiday weekday PM peak periods (10 percent). High winds, snow, and ice did not occur in 2012. Fog, frequently present during the summer season, rarely descends to and obstructs visibility at the road level. Thus, there were no low-visibility conditions in 2012.

No major new construction occurred on the freeway during the study year, 2012. Maintenance work zones on weekdays are timed to run between 9:00 am and 3:00 pm, with all lanes reopened to traffic by 3:00 pm. Thus, work zones are expected to have a negligible effect on PM peak-period operations. For the NB direction of US 101, there were 123 out of the 251 non-holiday PM peak periods (49 percent of the days) when a lane-blocking incident occurred at some time during the peak period. Demand does not vary greatly over the course of the year. The 5th percentile and the 95th percentile highest non-holiday weekday PM peak period demands span a range of plus or minus 9 percent of the median demand for the SB direction, and plus or minus 10 percent of the median for the NB direction.
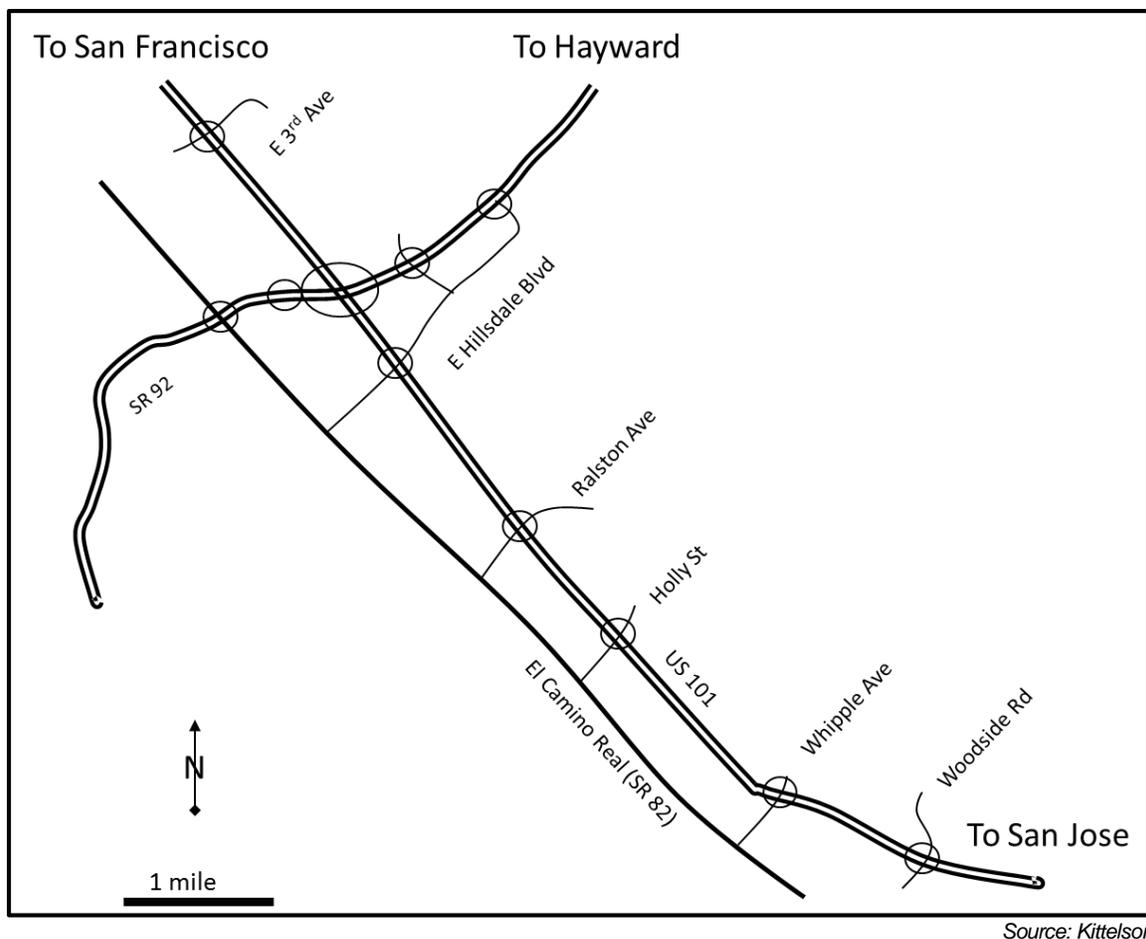
Figure 3-1. US 101 Study Corridor Geometry

The US 101 freeway is regularly congested in the NB direction during weekday PM peak periods. The lane reductions between the SR 92 interchange and the Third Avenue interchange are the bottlenecks. The freeway-to-freeway connector ramps at SR 92 also regularly experience queuing. Traffic is heavy in the SB direction as well, but it is not usually congested during weekday PM peak hours.

The corridor is coded in the PTV VISSIM Version 7.0, a microsimulation software package. The traffic modes modeled in this corridor consist of passenger cars (single and high-occupancy), trucks, and buses. The model was calibrated using 2012 PM peak data. The VISSIM software has various features to support modeling of R.E.S.C.U.M.E. applications:

1. A driver model interface that enables users to replace the innate driver behavior model in VISSIM with their own custom behavior model for all or selected vehicle types. The driver behavior was calibrated to match real driver behavior in the event an emergency vehicle is in the traffic mix.
2. Component Object Model (COM) API that enables users to dynamically modify VISSIM objects (vehicles, links, controls) during the simulation run. This functionality was used to initiate instances of crashes as well as custom functionalities with respect to vehicles and network objects (desired speed decisions, reduced speed areas, etc.)

3. Vehicle Actuated Programming (VAP) that enables users to write their own traffic-actuated signal controls. This functionality was used to enable ramp metering into the US101 freeway as is seen in real life. Adaptive ramp metering uses volume measurements from the main freeway to adaptively alter the signal-timing functionalities.

This corridor is part of the San Mateo Testbed that was originally developed for a project (2009-2013) funded by the Metropolitan Transportation Commission (MTC), the San Mateo County Transportation Authority, and the City and County Association of Governments of San Mateo County (CCAG). This testbed was calibrated based on observed traffic conditions in the field, such as volumes, travel time, bottleneck location, and duration of congestion. A series of operational and traffic management improvements were analyzed using the model, including ramp metering; auxiliary lanes; lane expansions; ramp closures due to short weaving, diverging, merging; and multimodal travel information.

Cluster analysis was done to define the top representative scenarios that are used for this study. This included all the logged days from the study year, which includes traffic measurements from special events, adverse weather conditions, and incidents. It was concluded that special event traffic was not common or critical to this study. Two representative incident days will be selected for developing scenarios for this study.

The corridor experienced 473 incidents in the NB direction during the PM peak period in 2012. Approximately half of these were crashes blocking one or more lanes. The median (50 percent) duration of incidents was 12 minutes. Travel time, spot speed, and mainline volumes are available for days with lane-blocking incidents, and were used for the incident calibration of the model adjustments. Volumes, travel times, and spot speed were drawn from the PeMS database for the PM peak period of that day. The free-flow speed and capacity adjustment factors recommended by Chapter 36 of the *2010 Highway Capacity Manual* were converted into the appropriate VISSIM car following parameters and desired speed profiles adjustments. The model ramp and mainline demands were factored to match the observed representative incident day mainline volumes.

The incident location, lanes blocked, start time, and duration were coded into the model for the two representative incidents. The model was run with the selected representative incident day demands and the end-to-end travel times compared to the observed times (averaged for each hour in the peak period). The desired speed profiles and car-following parameters were adjusted to meet the calibration criteria. The spot speeds observed by PeMS were examined to determine whether fine-tuning adjustments were also required for incident day operation.

3.2. Application Modeling

While the functionalities of the RESP-STG and INC-ZONE applications can be *prototyped* fully, some of these functionalities were only partially addressed in a VISSIM *simulation* environment. For example, the INC-ZONE application includes a functionality that will create audible threat alerts about an errant vehicle for the safety of personnel on scene. However, in a simulation environment, since the focus is on vehicles rather than on individuals, this functionality cannot be modeled. Similarly, functionalities that assess crashes (including secondary crashes) are difficult to model in a simulation environment since the innate driver model cannot consider crashes. Therefore, the analysis used surrogate safety measures that post-process the trajectory data to quantify crash reduction.

With regards to the INC-ZONE and RESP-STG applications, the following functions were included in the simulation model:

1. **Incident Creation:** Incidents are not inherent to simulation models. Therefore, hypothetical incidents need to be created within the simulation framework using alternate functionalities such as sudden lane closures or reduction in speed limits. In this particular application model, incidents were created dynamically by using vehicles that stop on a freeway lane at a desired time and position.

2. **INC-ZONE Function:** Simulating lane closures due to incidents will naturally cause vehicles to slow down and merge into the alternate lanes. The INC-ZONE application attempts to enhance their safety and mobility by giving early warning to vehicles. These warnings are generated using the individual vehicles' distance to the incident location and are provided as specific vehicle attributes or vehicle commands such as "Desired Lane" or "Desired Speed Distribution." The INC-ZONE function also comes with a user-defined delay time that defines the time between occurrence of an incident and start of the INC-ZONE function. In reality, this delay represents the time between an incident and the incident verification by the first responder.

3. **RESP-STG Function:** This functionality is simulated by automatically pairing incident location with responder-vehicle routing. Pre-defined responder vehicles reach the location from pre-defined start locations (fire stations). Some of the functionalities of the RESP-STG application, such as GIS-overlay-enabled development of the staging plan, cannot be simulated in a microscopic traffic environment. The simulation introduced a variable (user-entered) delay function from the start of the incident to the start of dispatch. Analysis of the potential benefits of shortening the dispatch time using the RESP-STG feature entailed using different values of dispatch delay to find at what value benefits of RESP-STG significantly affect the network performance.

4. **Performance Monitoring:** Performance monitoring mainly includes measures pertaining to the mobility and safety surrogate aspects of the corridor. The performance measures used in this impact assessment analysis are explained in a later section.

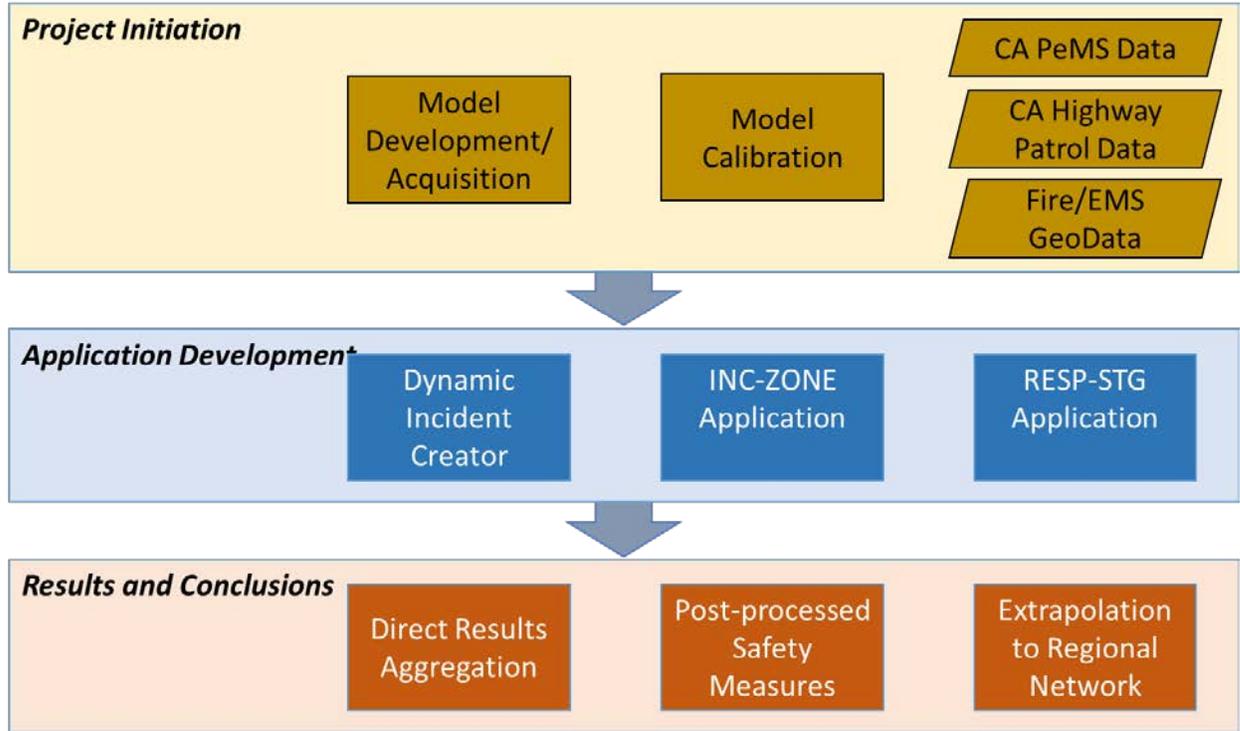Figure 3-2 provides the execution framework for the analysis.

Source: Booz Allen Hamilton

Figure 3-2. INC-ZONE and RESP-STG Corridor Modeling Framework

Table 3-2 lists the analysis and modeling strategies that were implemented to address the functionalities of INC-ZONE and RESP-STG based on the concept of operations definitions.

Table 3-2. INC-ZONE and RESP-STG Analysis Strategies

App.	Functionality	Corresponding Analysis/Modeling Strategy
INC-ZONE	Threat Determination	This is modeled by assessing the vehicle behavior that each vehicle should exhibit: 1. Changes in speed limit 2. Lane closures – Determine lane closures based on the MUTCD guidelines for temporary traffic control elements 3. Lane changes – Issue lane-change commands to vehicles upstream
	Oncoming Vehicle Alerts and Warnings	
	Responder Alerts and Warnings	Since responder alerts and warnings cannot be directly simulated in the VISSIM environment, surrogate measures were used to examine whether INC-ZONE will enhance safety at the incident location and for the oncoming vehicles. In other terms, the simulation directed vehicle behavior as if the drivers consistently followed the advice or warnings that would have been given by the INC-ZONE application. In consultation with *Surrogate Safety Measures from Traffic Simulation Models* (FHWA-RD-03-050), potential surrogate measures were identified and are described in the upcoming Performance Measures section.

App.	Functionality	Corresponding Analysis/Modeling Strategy
RESP-STG	Vehicle and Equipment Staging	This will be modeled in a limited functionality using a staging command that will be used to get the responder vehicles moving from a pre-determined starting location to the incident location. Functionalities, including providing advanced information to responders, staging plans, etc., cannot be modeled directly. A delay function was introduced that can vary the time between incident and dispatch. This delay function was used to justify the values that will extend the benefits of RESP-STG to the network-wide performance.
	Emergency Responder Status Reporting	This was modeled as a performance monitoring variable, reported as responder travel time to incident location. Features such as adequacy of dispatch, requirement of secondary dispatch, etc., cannot be modeled.

3.3. VISSIM Modeling

Both the INC-ZONE and RESP-STG applications were modeled in VISSIM 7.0 using its Component Object Modeling capability. Python 2.7.5 programming language was used in the application coding. The following provides specific application details.

3.3.1. INC-ZONE

Given that vehicle commands are used in the simulation of INC-ZONE rather than "alerts" or "advisories," specific characteristics of the commands can greatly influence the performance of the application. In the application modeled, three major types of commands are used by the INC-ZONE application:

1. Alteration of desired speed of vehicles
2. Alteration of desired lane to be taken by vehicles
3. Freezing of all the lane changes near the incident location to enhance safety.

The Appendix provides specific code snippets featuring these commands along with details on the preliminary analysis. The following is the pseudo-code for the INC-ZONE application.

Once the incident is initiated, its location is used for threat assessment of vehicles during each time-step of the simulation. Threat assessment entails classifying vehicles into three zones that require the application's action. These zones are defined using MUTCD guidelines on temporary zoning at work zones.

1. Zone one vehicles have a distance from the incident area that is the sum of buffer length, taper length, and advanced placement length and are heading to the incident area. At this zone, all vehicles on the incident lane are advised to start merging to the open lanes and slow down their speed to improve incident zone throughput.

2. Zone two vehicles have a distance from the incident area that is the sum of buffer length and taper length. Within this zone, all vehicles are enforced to the next set of speed reduction and guided to move to open lanes.

3. Zone three vehicles have just crossed the incident area. These vehicles have their speed and lane-change behavior set back to the default values.

3.3.2. RESP-STG

Responder vehicles are modeled using a heavy goods vehicle (HGV) to represent a fire truck or an ambulance of similar acceleration and maneuverability. HGV is a default vehicle type in VISSIM.

In the base case (i.e., when no RESP-STG is used), the responder vehicles are deployed after a defined time beyond the start of the incident. This time is representative of three variables:

1. Time taken for incident detection
2. Time taken for incident verification
3. Time taken for response dispatch.

Once the responder is dispatched from the closest fire/EMS station, the responder vehicle is routed to the incident location and staged near the incident. The responder vehicle behavior is chosen as the default behavior during its course in the base case.

For the test cases with RESP-STG modeling, the responder vehicles are deployed with a similar method, but use two data-sets to modify en route behavior:

1. **Routing Decision:** The routing decision involves the ramp choice to reach the incident location and is made based on data about average ramp speeds collected using Data Collection Measurements.
2. **Staging Decision:** The staging decision is made based on whether the incident lane is followed by a backlog of vehicles. The average queued data from vehicle records is used to make this judgment.

Further details about the applications' modeling are provided in the Appendix (Chapter 6).

3.4. Performance Measures

This section describes the major performance measures used for the analysis of INC-ZONE and RESP-STG. These measures, pertaining to mobility and safety with indirect environmental consequences, were used to assess the impacts of these applications. To extract the required performance measures from VISSIM simulations, a specific evaluation set was configured for the simulations. This included the following features:

1. **Data Collection:** The purpose of this feature is to collect data from specific points defined as data collection points along the freeway section. Data collection points were set up on a lane-by-lane basis at every 0.5 mile. The points were set up to measure acceleration, distance between vehicles, vehicle occupancy, queued delay and average speed for these 0.5-mile-long sections.
2. **Delay Measurement:** VISSIM can directly output total vehicle delay and average vehicle delay at specific time intervals, between specific delay measurement points. This interval was set at 30 minutes.

3. **Vehicle Network Performance:** This data included network metrics such as delay, speed, number of stops, travel time, and latent demand at specific intervals. Latent demand is defined as the unserved demand left at the end of the simulation period.
4. **Lane Changes:** This output dataset tracks and stores all the lane changes happening withinspecified time and distance intervals.
5. **Vehicle Records:** This dataset stores raw data on the vehicles at specific intervals. Data was collected at 20-second intervals for the incident duration and consisted of link and lane characteristics, speed, position, following distance, queued status, and lane-change status of all vehicles.

It is to be noted that the term *market penetration* has been used in this report to represent an integrated factor that captures the percentage of vehicles that follows the commands generated by the R.E.S.C.U.M.E. applications bundle.

To describe the performance of the different R.E.S.C.U.M.E. applications under different operational conditions and market penetration rates, several performance measures were defined based on the scope and impact area for which each of them applies (as shown in Table 3-3). The performance measures are classified into three groups according to their scope:

1. **Network-Wide Performance Measures:** This scope represents the measures that work on a network level and shows the improvements over the entire network that includes the 8.5-mile freeway and all associated inlets and outlets.
2. **Incident-Zone Level Performance Measures:** This scope represents the measures that describe the application performance across the 0.5-mile sublink that contains the incident at its downstream end, since most of the R.E.S.C.U.M.E. applications' behavior occurs upstream of the incident.
3. **Individual User Performance Measures:** This scope represents the performance of "users" of the R.E.S.C.U.M.E. applications in contrast to the "non-users." In other words, it describes the benefits that a vehicle would have if it followed the INC-ZONE and RESP-STG commands over vehicles that did not have the technology or did not follow the commands. These performance measures are likely to lead to faster adoption of the technology.

Table 3-3. Performance Measures Classified According to the Scope

Scope	Category	Impact Area	
		Mobility/Environmental	**Safety**
Network-wide	INC-ZONE impacts	Reduction in Average Delay of the Network	
		Increase in Average Speed of the Network	
	RESP-STG impacts	Reduction in Average Delay of the Network	
		Increase in Average Speed of the Network	
Incident Zone Level	INC-ZONE impacts	Increase in Section Throughput	Reduction in Maximum Deceleration

Scope	Category	Impact Area	
		Mobility/Environmental	**Safety**
			Reduction in Average Sublink Speed
Individual User Level	INC-ZONE users	Increase in Average Speed	Increase in Average Following Distance
	RESP-STG users (responders)	Reduction in Travel Time	Reduction in Number of Stops

Table 3-4 represents the performance measures analyzed in this study classified based on their impact area, the corresponding application, and the scope. The analysis included five measures based on mobility and environment and four measures based on safety. The table gives a brief description of these measures including their significance in the current analysis. More detailed definitions of these performance measures are provided later in this section.

Table 3-4. Performance Measures Description Based on Impact Area

Impact Area	Measure	Description	Application	Scope
Mobility/ Environmental	Reduction in Average Delay	Shows the average deviation in total travel-time of individual vehicles between their origin and destination from free-flow conditions and represents improved mobility.	INC-ZONE/ RESP-STG	Network-wide
	Increase in Average Speed	Shows the deviation in average spot speeds of vehicles during their entire travel from the base case.		
	Increase in Section Throughput	Shows the number of vehicles that can pass through the incident zone in a given time.	INC-ZONE	Incident-zone level
	Increase in Average Speed	Shows the increase in average speed of an individual vehicle in the simulation when compared to the base case.	INC-ZONE	Individual user level
	Reduction in Travel Time	Shows the reduction in time taken by emergency vehicles to move between the fire/EMS station and the incident location.	RESP-STG	
Safety	Reduction in Maximum Deceleration	Maximum deceleration in the incident zone characterizes the level of hard brakings in the section.	INC-ZONE	Incident-zone level
	Reduction in Average Sublink Speed	Lesser average speed of vehicles in the sublink		

Impact Area	Measure	Description	Application	Scope
		enhances safety of the personnel in the incident area.		
	Increase in Average Following Distance	A higher average following distance reduces the probability of secondary crashes as drivers get longer time to react.		
	Reduction in Number of Stops	Reduction in number of stops for the emergency vehicle means lesser interruptions in their movement through the network, which represents fewer crashes involving emergency vehicles.	RESP-STG	Individual user level

The following is a detailed description of the performance measures used in the analysis.

1. **Reduction in Average Delay:** At a network-wide level, reduction in average delay is computed using percentage deviation in the overall average delay per vehicle in the simulation for each individual case over the do-nothing base case. Average delay is computed using averaged values of individual vehicle delays over the entire simulation period.

2. **Increase in Average Speed:** Average speed of vehicles in the simulation represents the average of spot speeds of individual vehicles throughout the period it remains in the simulation. At a network level, this performance measure represents the percentage deviation of the average speed of vehicles in the simulation for each individual case over the base case. At a user level, increase in average speed represents the difference in average speed of equipped vehicles versus the average speed of non-equipped vehicles under the same operational condition.

3. **Increase in Section Throughput:** Throughput of the incident zone defines the number of vehicles that can successfully pass through the incident zone in a given time period. A higher value of throughput characterizes better mobility. The change in throughput reported in this analysis is defined as the percentage deviation of the throughput (in terms of vehicles/hour) from the base case.

4. **Reduction in Travel Time:** This performance measure represent the reduction in average time taken by the emergency vehicles to travel from the nearest fire/EMS station to the incident location, and is used to analyze the effectiveness of the RESP-STG application.

5. **Reduction in Maximum Deceleration:** Sudden deceleration of vehicles within the incident zone can mean unsafe scenarios for the emergency personnel on the scene as well as a trigger for secondary crashes. VISSIM simulations represent a range of driver characteristics in terms of their speed selection, following distance, or look-ahead characteristics. The maximum of the average deceleration of vehicles within the 0.5-mile sublink of the incident is measured and compared against the base-case scenario. A negative change in maximum deceleration implies increased safety.

6. **Reduction in Average Sublink Speed:** Sublink speed is measured as the average speed of vehicles traveling in the incident zone (i.e., 0.5-mile sublink). The lower the

average speed of vehicles near the incident, the safer it is for the emergency personnel on the scene. This metric is also measured as the percentage deviation from the base case.

7. **Increase in Average Following Distance:** This measure is a proxy for the safety of vehicles within the incident zone. A greater following distance denotes a greater time headway between vehicles and lesser chance for secondary crashes. In this metric, the average following distance of vehicles was compared between equipped and non-equipped vehicles under the same operational condition.

8. **Reduction in Number of Stops:** This performance measure is a safety metric for analyzing the effectiveness of the RESP-STG application. It involves comparing the number of stops that the emergency vehicle makes during its trip. The comparison is made over the number of stops during the do-nothing case. A stop is defined as a specific trajectory event when the speed of a vehicle drops below 10 miles per hour.

3.4.1. Visual Audits and Vehicle Records Analysis

Visual audits and vehicle records analysis were an essential part of analyzing the results produced by the simulation, and were done when the aggregate simulation results deviated from a specific trend. For example, if the values of a performance measure at 50-percent market penetration were not between the values produced at 25- and 75-percent market penetrations, this advanced analysis was used to verify the results and evaluate the rationale behind the observations. The visual audits and vehicle records analysis were only done for operational conditions that produced results outside of a trend.

Visual audits involve analyzing the vehicle behavior during simulations visually by using color-coded vehicles to differentiate between connected and non-connected vehicles. The Quick-view function within VISSIM 7 is used to track characteristics of vehicles such as speed, desired speed, and desired lane. This method of analysis helps to identify whether vehicles that receive commands to change lanes are actually doing so, or if not, the reason for not changing lanes (e.g., inability to find a minimum gap). To supplement this, vehicle records were also analyzed so that statistics could be drawn for this vehicle behavior.

3.5. Scenarios and Operational Conditions

To study the effectiveness of the INC-ZONE and RESP-STG applications, two different operational conditions were analyzed for two different incident conditions. These four combinations of operational and incident conditions were simulated for five levels of market penetration in addition to the "zero" market penetration being the base case. Simulations were performed for these 24 scenarios, replicated 10 times with random starting seeds to accumulate statistically significant results. Figure 3-3 shows the operational conditions that are studied in this report.
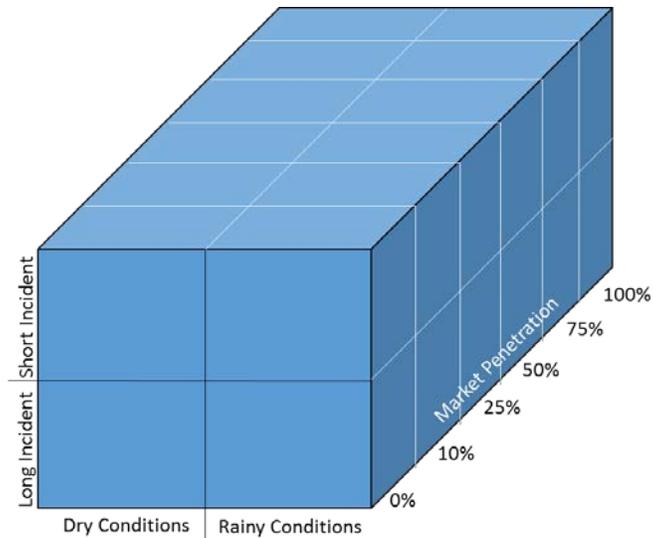
Source: Booz Allen Hamilton

Figure 3-3. Operational Conditions Analyzed

As far as the operational conditions are concerned, the short incident represents a single-lane closure for the duration of 30 minutes and the long incident represents a single-lane closure for a duration of 60 minutes. The network was calibrated for both dry and rainy conditions, where dry represented no precipitation and high visibility, and rainy represented an hourly precipitation of 1/10 inch. The network is calibrated using *Highway Capacity Manual* guidelines, where Chapter 37 was used for free-flow calibration and Chapter 10 was used for active incident calibration. The capacity ratios used were 1:0.98 for dry and rainy conditions and 1:0.81 for incident conditions.

3.6. Simulation and Incident Details

Each simulation is 7 hours long and represents a 5-hour PM peak simulation along with a 1-hour warm-up time to achieve the required traffic conditions in the network, and another 1-hour cool-down time in the end to serve all the unserved demand from the previous period. The 5 hours represent the evening peak traffic on the US 101 network from 2:30 pm to 7:30 pm on a typical weekday. For the short incident case, a single-lane incident was simulated as a lane-closure for a length of 100 feet on the mainline for 30 minutes. For the long incident case, this duration was 60 minutes. The incident start time is set at 3:30 pm for both cases, and the location of the incident is on US 101 NB, between the entrance ramp from East Hillsdale Boulevard and exit ramp to J. Arthur Younger Freeway (SR-92) at a distance of 600 feet from the former. The overall length of this link is around 900 feet and is sandwiched between two on-ramps and an off-ramp. This set up causes heavy congestion upstream of the link because of the incident.

Figure 3-4 shows the selected location of the incident as well as the nearest fire/EMS station to deploy emergency vehicles.
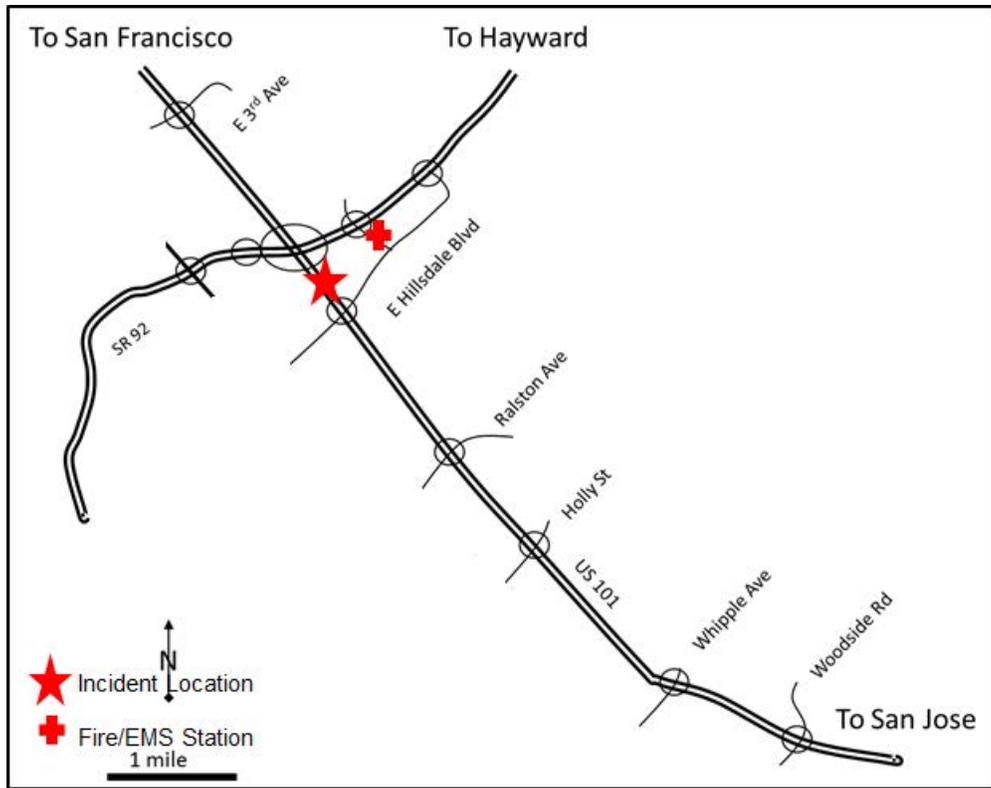
Figure 3-4. Study Corridor Showing Incident Location and the Fire/EMS Station

The next chapter describes the performance measures for each case. This includes the potential user impacts for vehicles that are equipped with the technology and comply with its messages, network-wide performance measures, mobility measures within the incident zone (sublink), and the surrogate safety measures within the incident sublink.

Chapter 4. Analysis and Results

This chapter describes the modeling analysis and presents the results for each analyzed scenario under different scopes, ranging from network-wide impacts to incident-zone level impacts to individual user benefits.

4.1. Network-wide Performance Measures

The metrics used in the network-wide impact analyses are reduction in average vehicle delay and increase in average vehicle travel speed. Resultsshown in this section are only for the period of the incident and do not cover the overall duration of the simulation. This is for an easier demonstration of the impacts of the applications on network mobility and safety since the INC-ZONE application does not work outside ofthe incident duration. Each scenario is analyzed with five different levels of market penetration (i.e., 10 percent, 25 percent, 50 percent, 75 percent, and 100 percent) and compared with the base-line "do-nothing" case. The network-wide performance measures were analyzed using the INC-ZONE application only, since the RESP-STG application is specific to the movement of the emergency vehicle class and does not affect the overall performance of the network.

Note that the results shown in this section have a geographic range extending throughout the corridor and a temporal range equivalent to the incident duration to effectively demonstrate the impacts of the system. Barplots are used in the following sections to demonstrate the impact of the application along with dotted lines that represent trendlines.
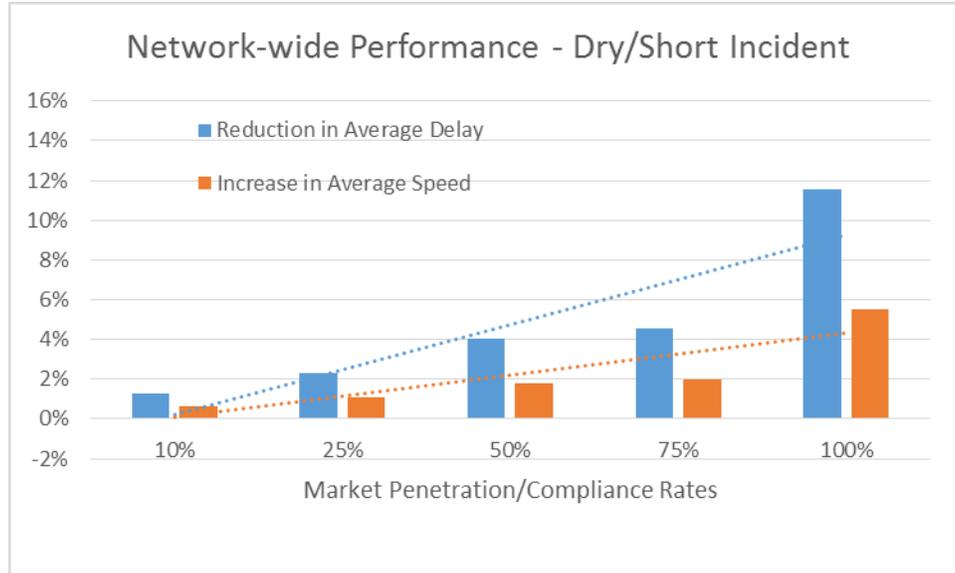
4.1.1. Dry Conditions

The network that was calibrated using the dry conditions was simulated for two different operational conditions as specified in Chapter 3—a short incident (involving a single-lane closure for 30 minutes) and a long incident (involving a single-lane closure for 60 minutes). The results are provided below along with a discussion.

4.1.1.1 Short Incident Duration

Under short-incident conditions, the applications were able to bring considerable improvement to the network mobility, safety, and indirect environmental measures. Two major measures analyzed for network-wide impacts are the average reduction in vehicle delay and the average increase in vehicle speed. Figure 4-1 demonstrates these performance measures for different levels of market penetration. These values represent the percentage improvement from the base case in which INC-ZONE and RESP-STG applications were absent.

Average reduction in delay, which is a direct measure of improved mobility and an indirect environmental measure linked to the improvement in fuel efficiency and emissions, is shown to be 1.5 percent at 10-percent market penetration. This reduction rises to 11.5 percent at 100-percent market

penetration. The highest improvement is between 75-percent (4.2-percent reduction in delay) and 100-percent market penetration. Average increase in vehicle speed also shows a similar trend. At 10-percent market penetration, there is only 0.8-percent improvement in average vehicle speed. This gradually increases to 5.5-percent improvement at 100-percent market penetration. The highest improvement is when the market penetration increases from 75 percent to 100 percent.
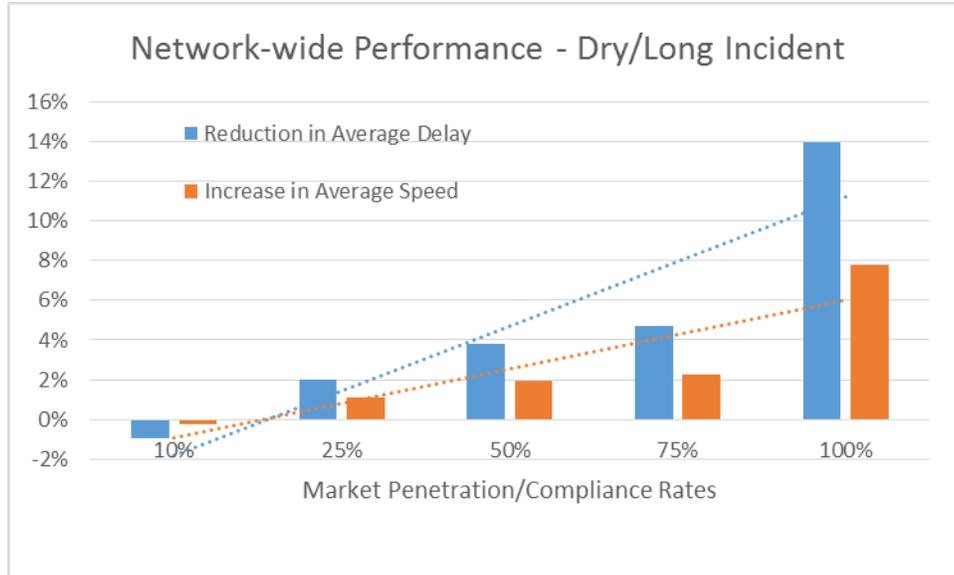
Figure 4-1. Dry/Short Incident Case: Network-wide Performance Measures

4.1.1.2   Long Incident Duration

Figure 4-2 shows the two network-wide performance measures under dry conditions when there is a long incident (60 minutes). Under 10-percent market penetration, there is a slight disbenefit in terms of both average vehicle delay and average vehicle speed. The average vehicle delay increases by 0.8 percent, and the average vehicle speed decreases by 0.1 percent. These disbenefits are negligible when compared to the benefits achieved at higher levels of market penetration. Data from individual vehicle records suggests that these disbenefits are a result of the behavior of non-equipped vehicles that follow equipped vehicles moving to less desired lanes, causing additional delays.

For market penetration beyond 25 percent, there are network-wide benefits. The average reduction in vehicle delay ranges from 2 percent for 25-percent market penetration to 14 percent for 100-percent market penetration. Like in the short incident case, the highest jump in benefits is between 75-percent and 100-percent market penetration. Similarly, for increase in average vehicle speed, the performance varies from 1 percent for 25-percent market penetration to 8 percent for 100-percent market penetration.
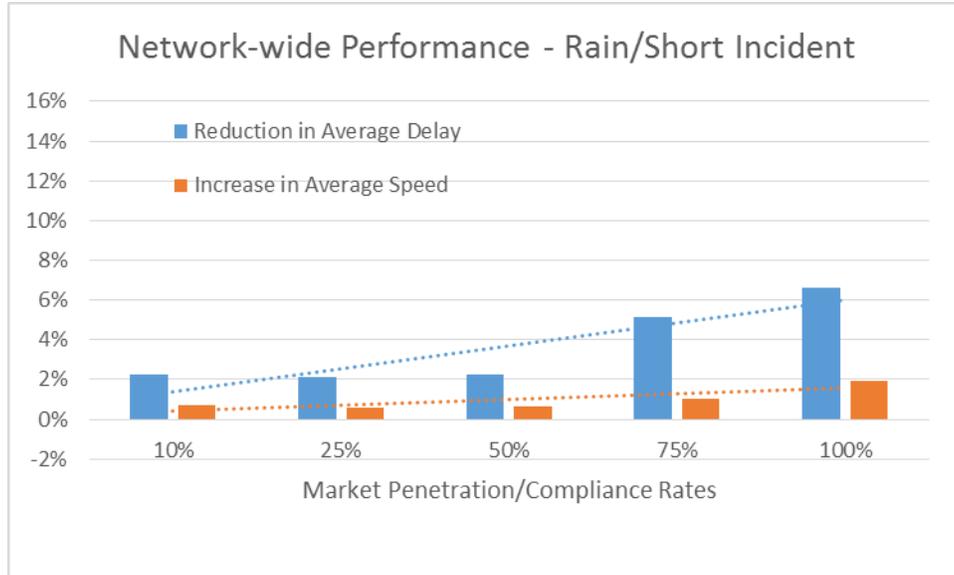
Figure 4-2. Dry/Long Incident Case: Network-wide Performance Measures

4.1.2. Rainy Conditions

In this particular case, the network was calibrated using data collected during rainy days at the particular geographic location. The following are the results for the two operational conditions, along with a discussion on notable trends.

4.1.2.1 Short Incident Duration

Figure 4-3 demonstrates the network-wide impact of the INC-ZONE and RESP-STG applications under rainy conditions with a short 30-minute incident. Both performance measures, namely the average reduction in vehicle delay and the average increase in vehicle speed, improve when a higher percentage of vehicles use the applications. For example, at 10-percent market penetration, the average reduction in vehicle delay is found to be 2.3 percent, versus 6.6 percent at 100-percent market penetration. Similarly, the average increase in vehicle speed varies between 0.7 percent (at 25-percent market penetration) and 2 percent (at 100-percent market penetration).
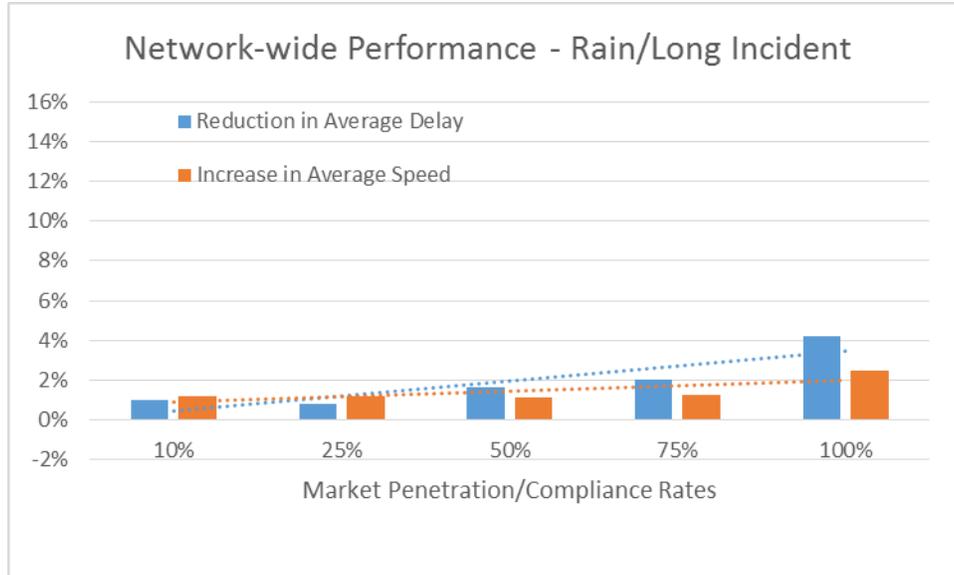
Source: Booz Allen Hamilton

Figure 4-3. Rain/Short Incident Case: Network-wide Performance Measures

4.1.2.2   Long Incident Duration

Figure 4-4 shows the network-wide performance for rainy conditions with a long incident. As shown in the previous case, the average reduction in vehicle delay and the average increase in vehicle speed have positive trendlines with the increase in market penetration. The average reduction in vehicle delay ranges between 0.8 percent and 4.2 percent, and the average increase in vehicle speed is between 1.2 percent and 2.5 percent. Note that linear trendlines were used for easier demonstration of results, and therefore, they do not account for absolute differences between different levels of market penetration.

Figure 4-4. Rain/Long Incident Case: Network-wide Performance Measures

4.1.3. Sensitivity to Operational Conditions

Figure 4-5 shows a comparison of various performance measures that are collected at a network level for 100-percent market penetration under the four different operational conditions. INC-ZONE provided more "percentage" improvement in the dry case than in the rainy case. This was primarily due to the fact that drivers are generally cautious about their look-ahead characteristics when driving in rain, which reduced the effectiveness of the applications. Also, for rainy conditions, a long incident yielded only little benefits with respect to reduction in average vehicle delay and reduction in average vehicle speed. This is due to the longer queues of vehicles caused by the longer incident. For dry conditions, a long incident caused the applications to provide better benefits than short incident since the base case had longer delays for longer incidents.
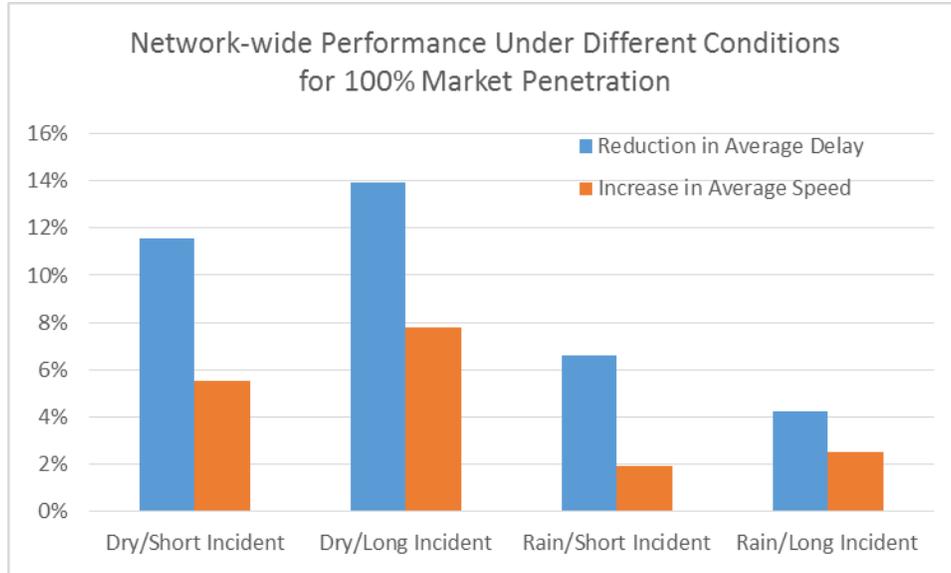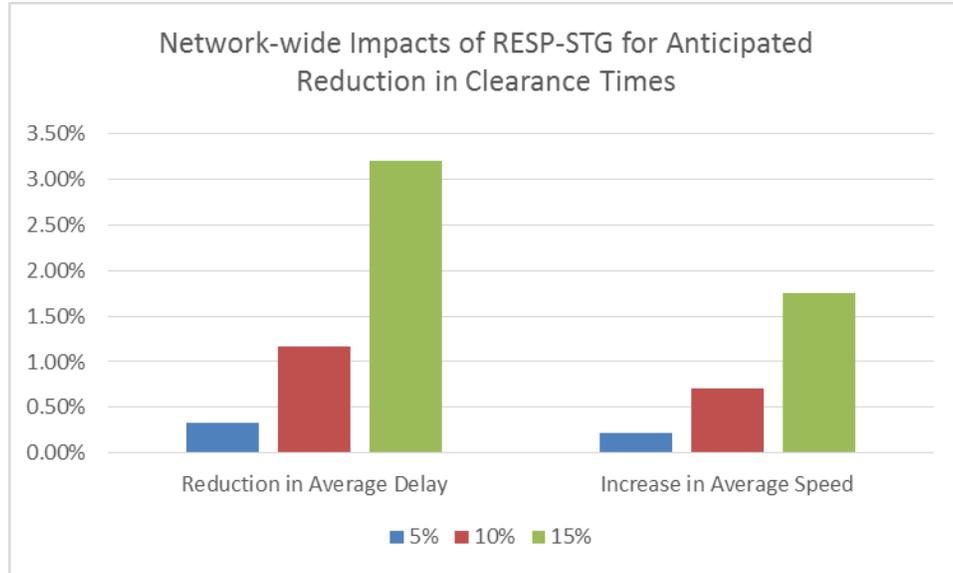
Source: Booz Allen Hamilton

Figure 4-5. Comparison of Performance Measures Under Different Operational Conditions

4.1.4. RESP-STG Benefits

In this analysis, several of the RESP-STG functionalities that relate to responder decision making were not modeled due to scope and software limitations. RESP-STG includes advanced functionalities for responders to receive data on the incident while en route so that they can get to the incident and stage their equipment faster. In the real world, these additional functionalities might help responders to deploy earlier and emergency vehicles to reach the incident location faster. An aggregate of these times is modeled in the simulation as a reduction in clearance times, which is reflected as the reduction in the duration of the simulated incident. This reduction in clearance time was used as a sensitivity test factor against which network mobility benefits were compared. This section highlights network-wide performance measures based on RESP-STG's potential reduction of the incident clearance time by 5 percent, 10 percent, and 15 percent. These clearance times are assumed to factor for all the advantages emergency responders would have when the RESP-STG application is being used to reach the incident location sooner. A microscopic analysis of responder travel when the RESP-STG application is used is given in a later section on the user benefits of RESP-STG.

Figure 4-6 shows the average reductions in delay and increase in travel speed of vehicles. The three bars demonstrate the results for different levels of anticipated reduction in clearance times (characterized by the reduction in the duration of the simulated incident). On average, a 5-percent reduction in clearance time can impact the overall network performance by 0.4 percent. This benefit increases gradually with reduction in clearance times. If the clearance times are reduced by 15 percent, reduction in network delay and increase in average speed were found to be 3.2 percent and 1.7 percent respectively.

Source: Booz Allen Hamilton

Figure 4-6. Network-wide Performance Measures for Various Values of Reduction in Clearance Times

# 4.2. Incident Zone Level Benefits – Mobility

This section summarizes the mobility impacts of the INC-ZONE application in the incident zone as demonstrated in Figure 4-7 through Figure 4-10. The performance measure analyzed was the increase in throughput of the incident zone. While this directly demonstrates the mobility-based performance of the applications, it indirectly indicates potential environmental effects too. For example, a greater throughput represents lesser emissions around the incident zone since fewer vehicles are idling approaching the incident area. The results shown in this section pertain to the sublink defined as the 0.5-mile segment of the freeway that is upstream of the incident, including the incident area. This area is hereafter referred to as "incident zone." Further definitions of these performance measures are given in the Performance Measures section. Two different conditions are analyzed with two different durations of incidents. They are described below.

4.2.1. Dry Conditions

The following describes the mobility benefits provided by the INC-ZONE application to the overall performance of the incident zone sublink under dry conditions.

4.2.1.1   Short Incident Duration

During the short incident duration, there was an increase in throughput when the INC-ZONE application was used. This impact increased with the increase in the level of market penetration. The increase in throughput of the incident zone ranged from 1 percent (for 10-percent market penetration) to 14 percent (for 100-percent market penetration). The biggest jump in this metric is when the market penetration increased from 75 percent to 100 percent due to the fact that the vehicle's behavior is optimized around the incident zone.
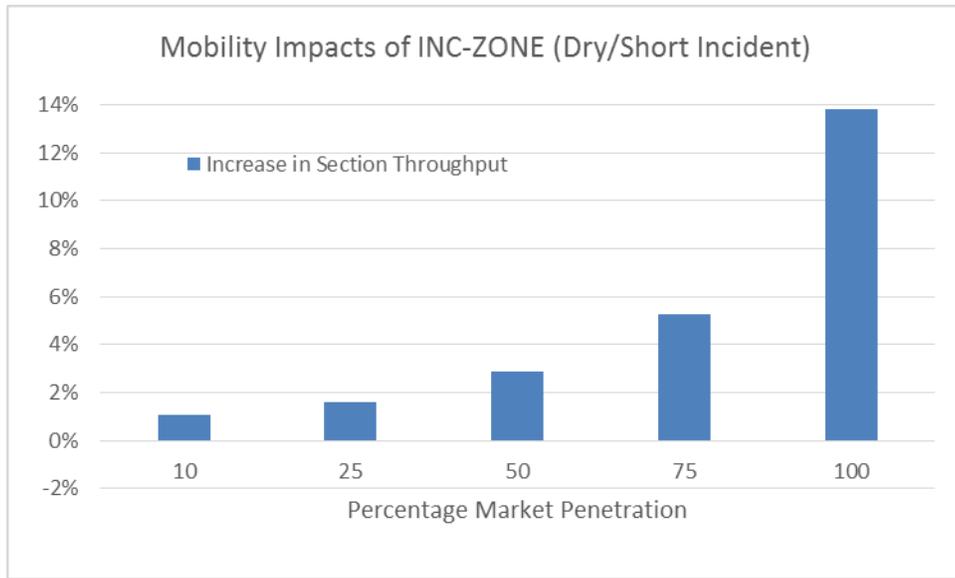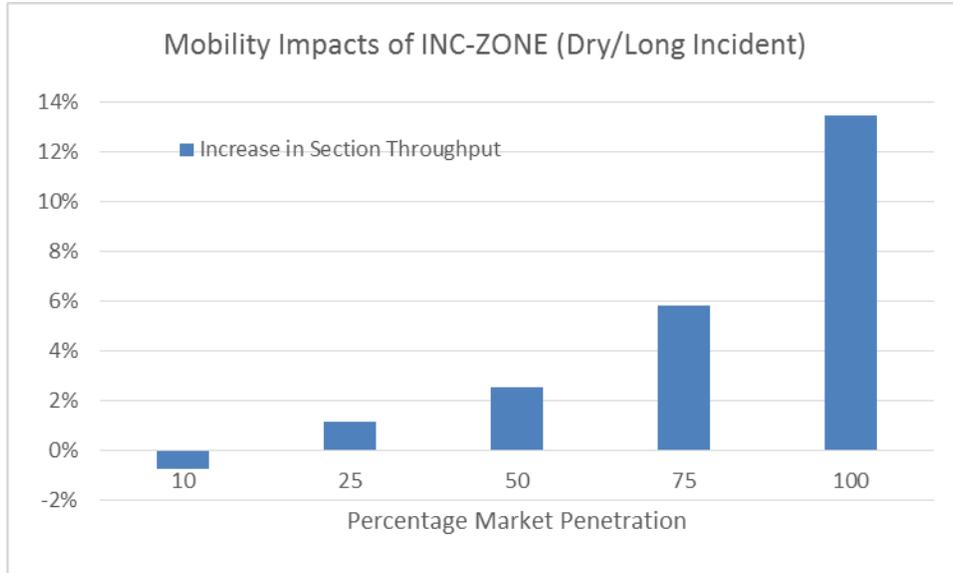
Source: Booz Allen Hamilton

Figure 4-7. Dry/Short Incident Case: Mobility Improvement

4.2.1.2 Long Incident Duration

During the long incident duration, the increase in throughput of the incident zone is an increasing function of INC-ZONE's market penetration. Interestingly, at 10-percent market penetration, the mobility measure is slightly less than the "do-nothing" scenario. This is due to the fact that the long incident adds a backup of vehicles beyond the extent of the INC-ZONE command broadcast (as prescribed by the R.E.S.C.U.M.E. System Design Document[5]). For higher levels of market penetration, this backup is absent since more vehicles are receiving the INC-ZONE commands and thus behaving in an optimal way. The highest increase in thoughput is for 100-percent market penetration at 14 percent over the base case.

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[5] *R.E.S.C.U.M.E. Prototype System Design Document, Final Report*; Battelle; April 11, 2014

Mobility Impacts of INC-ZONE (Dry/Long Incident)

■ Increase in Section Throughput

Percentage Market Penetration
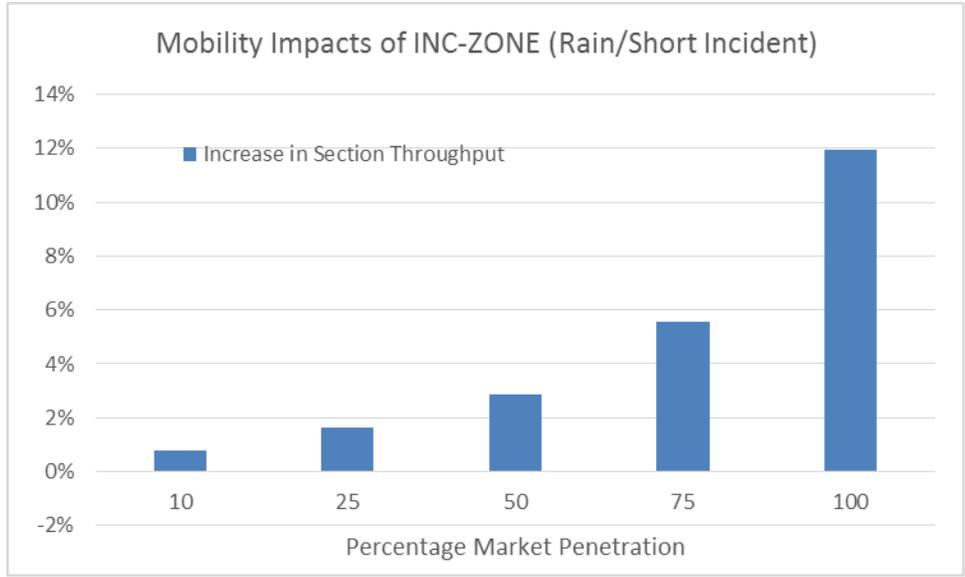
Source: Booz Allen Hamilton

Figure 4-8. Dry/Long Incident Case: Mobility Improvement

4.2.2. Rainy Conditions

The following describes the mobility benefits resulting from the INC-ZONE application to the overall performance of the incident zone sublink under rainy conditions.

4.2.2.1 Short Incident Duration

Under the short incident case for rainy conditions, the throughput of the incident zone increases with growing market penetration, as shown in Figure 4-9. The values of this performance measure increase from 1 percent at 10-percent market penetration to 12 percent at 100-percent market penetration. The highest jump in throughput is when the market penetration increases from 75 percent to 100 percent.
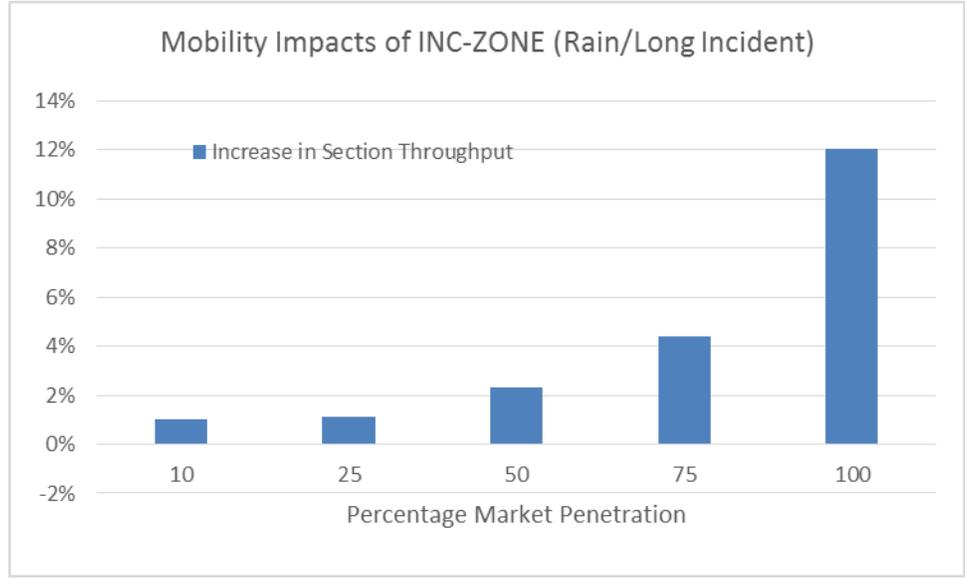
Source: Booz Allen Hamilton

Figure 4-9. Rain/Short Incident Case: Mobility Improvement

4.2.2.2   Long Incident Duration

Under long incident cases for rainy conditions, the results were similar to the previous case (see Figure 4-10). The values show an increasing trend with the least being 1 percent for 10-percent market penetration and 12 percent for 100-percent market penetration.

Source: Booz Allen Hamilton

Figure 4-10. Rain/Long Incident Case: Mobility Improvement

4.3. Incident Zone Level Benefits – Safety

In terms of safety-related metrics, the two important surrogate safety measures analyzed were reduction in maximum deceleration within the incident zone and the reduction in incident zone sublink speed. Both metrics are important in enhancing the safety of an incident zone. Reduction in maximum deceleration will help mitigate secondary crashes including rear-end crashes. Similarly, reduction in average sublink speed enhances the safety of the incident area including responder or emergency personnel safety. Note that, from a mobility perspective, INC-ZONE improved the average *network-wide* speed of the vehicles, whereas from a safety perspective, INC-ZONE reduced the average speed of vehicles *in the incident zone*. The lane and speed guidance provided by INC-ZONE contributes to reducing congestion upstream of the incident, thus achieving network-wide mobility benefits. In the base-case, the vehicles in the incident area had higher speeds since they were not governed by the INC-ZONE messages, and the vehicles upstream were slower due to congestion. This section provides the results for the various analyzed operational conditions.

4.3.1. Dry Conditions

The following are the results for dry conditions.

4.3.1.1 Short Incident Duration

Under short incident conditions, both performance measures—reduction in maximum deceleration and reduction in average sublink speed—increase with the rise in market penetration, as shown in Figure 4-11. The reduction in maximum deceleration and the reduction in average sublink speeds are calculated using instantaneous vehicle records collected within 0.5 mile upstream of the incident location. As the market penetration increases, the maximum value of deceleration within the sublink is reduced. For example, at 10-percent market penetration, this reduction was only 1 percent, but at 100-percent market penetration, this reduction was almost 82 percent. The reduction in sublink speed was averaged across all vehicles within the region. The reduction in average sublink speed ranged from 1 percent at 10-percent market penetration to nearly 11 percent at 100-percent market penetration.
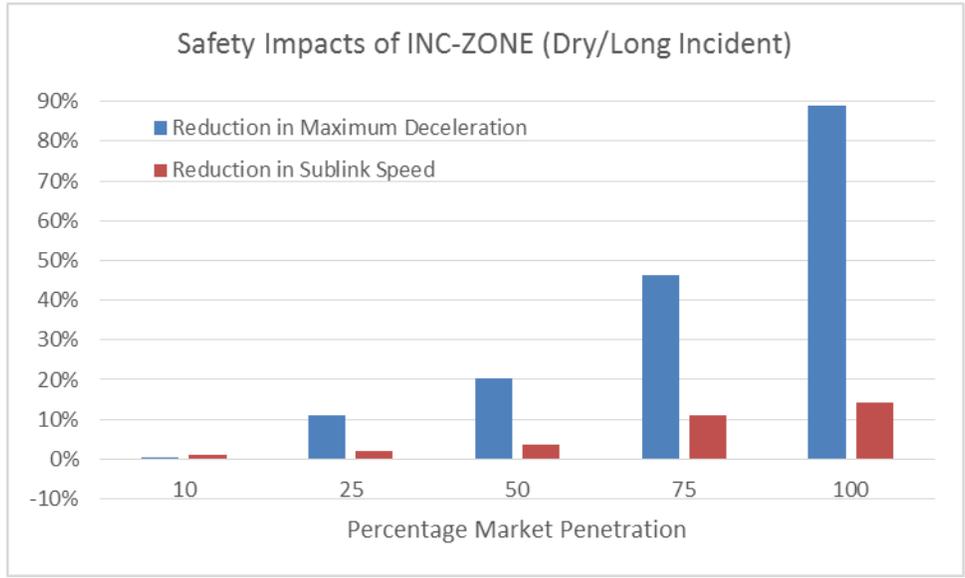
Safety Impacts of INC-ZONE (Dry/Short Incident)
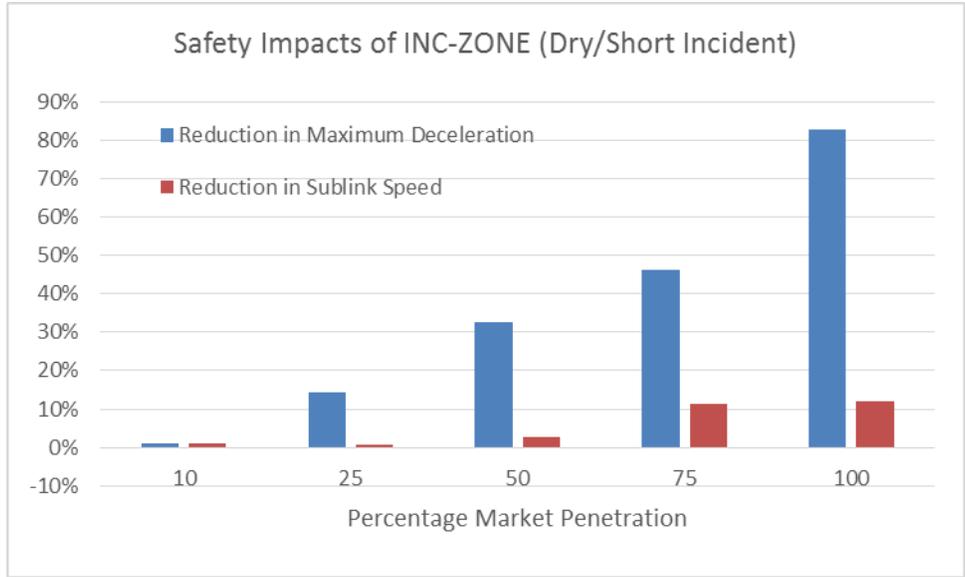
Source: Booz Allen Hamilton

Figure 4-11. Dry/Short Incident Case: Safety Improvement

4.3.1.2   Long Incident Duration

Figure 4-12 shows the results for long incident under dry conditions. Although the trend of reduction in maximum deceleration and average sublink speeds remain similar to the short incident case, the absolute values are lower than those of the short incident case. The reduction in maximum deceleration ranged between 0 percent at 10-percent market penetration to almost 88 percent at 100-percent market penetration. Similarly, the range of reduction in sublink speed was between 1 percent and 13 percent.

Safety Impacts of INC-ZONE (Dry/Long Incident)

Source: Booz Allen Hamilton

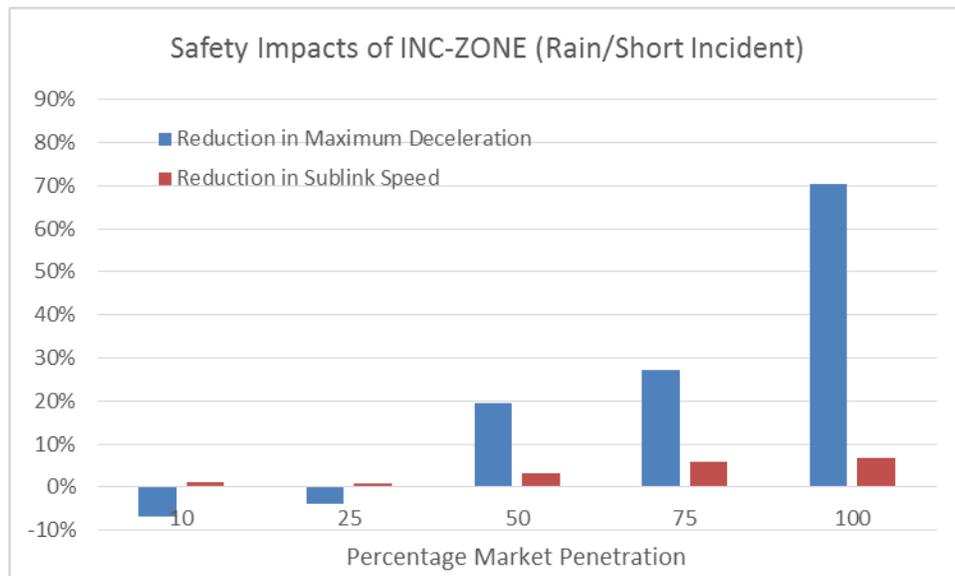**Figure 4-12. Dry/Long Incident Case: Safety Improvement**

4.3.2. Rainy Conditions

The following are the INC-ZONE-related safety impacts under rainy conditions.

4.3.2.1 Short Incident Duration

Figure 4-13 shows the range of safety benefits associated with the short incident case. Unlike dry conditions, the maximum deceleration value is shown to have increased under lower levels of market penetration. But this effect vanished when the market penetration increased beyond 25 percent. Analysis of vehicle records suggested that, under rainy conditions, non-connected vehicles had to decelerate suddenly prior to the incident area since longer gaps required to merge lanes were not available in the open lanes. This behavior is absent at higher levels of market penetration when more vehicles changed lanes to open lanes at a farther upstream point due to the INC-ZONE application commands. As far as the range of values is concerned, the maximum deceleration in the sublink ranges between a positive 6 percent value to a negative 70 percent value when compared to the "do-nothing" case.

Figure 4-13 also shows the range of reduction in average sublink speed under different levels of market penetration. These values range from 1 percent for 10-percent market penetration to 7 percent for 100-percent market penetration.
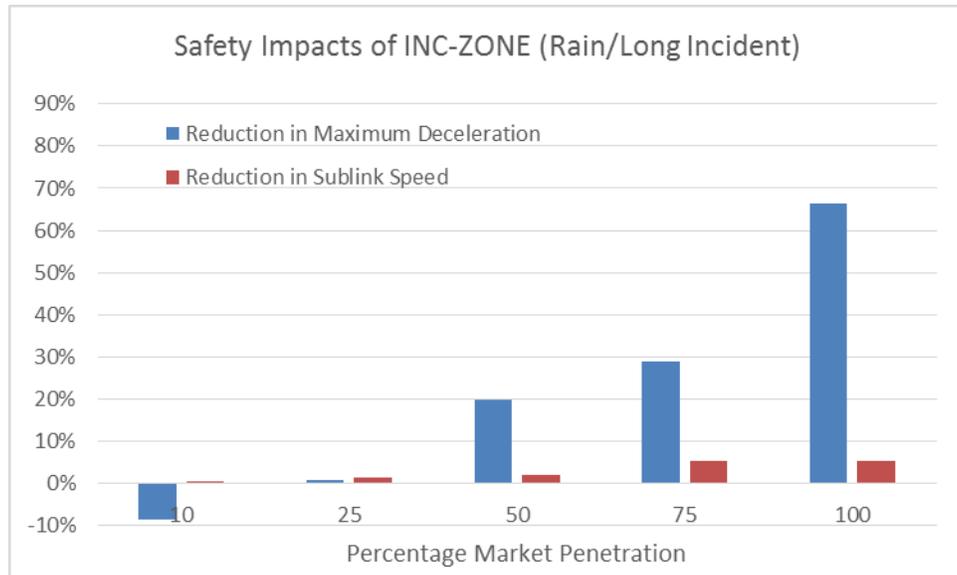

Source: Booz Allen Hamilton

Figure 4-13. Rain/Short Incident Case: Safety Improvement

4.3.2.2 Long Incident Duration

For the long incident case, the range of safety benefits was smaller than for short incidents, as shown in Figure 4-14. In terms of the maximum deceleration within the sublink, the values ranged from an increase of 9 percent at 10-percent market penetration to a reduction of 66 percent at 100-percent market penetration. The reduction in average sublink speed ranged between 1 percent and 5 percent for different levels of market penetration.

Source: Booz Allen Hamilton

Figure 4-14. Rain/Long Incident Case: Safety Improvement

4.4. User Benefits

This section discusses the impacts for users of the system. System users include the vehicles that are subject to the INC-ZONE commands such as change in desired speed and change in desired lane. The users of the RESP-STG system consist of the emergency vehicles.

The performance measures for the application users are identified from the microsimulation's individual vehicle records that are collected during the simulation and then filtered to classify "equipped" and "non-equipped" vehicles. In this context, equipped vehicles represent the class of vehicles that have the INC-ZONE application and follow the guidance that it provides. All other vehicles are grouped under the "non-equipped" vehicle class. To demonstrate the benefits gained by equipped vehicles, their performance measures are compared against the measures from non-equipped vehicles and represented as percentage improvements.

4.4.1. Dry Conditions

The following describes the three performance measures that were measured with respect to user benefits for the INC-ZONE system under dry weather conditions.

4.4.1.1 Short Incident Duration

Under short incident conditions, INC-ZONE provides improvement in direct mobility and safety as well as indirect environmental benefits. Figure 4-15 shows the percentage benefits achieved by equipped road users when compared to non-equipped road users. Even at 10-percent market penetration, the equipped users achieve at least 15-percent improvement in travel speed within the 1-mile zone of the

incident. Similarly, the improvement in average following distance is 7.5 percent at 10-percent market penetration.

These values gradually increase with rising market penetration. At 100-percent market penetration, all vehicles are equipped, and thus all road users achieve similar benefits. At 75-percent market penetration, the improvement in average speed of equipped vehicles is almost 34 percent when compared to the average speed of non-equipped vehicles. Therefore, it can be inferred that as market penetration goes up, the performance gap between equipped and non-equipped vehicles widens. This is potentially due to the fact that non-equipped vehicles tend to deviate farther from the equipped vehicles' behavior in terms of lane usage and desired speeds. The largest benefits for equipped vehicles in terms of increase in average following distance is 15 percent when compared to non-equipped vehicles.
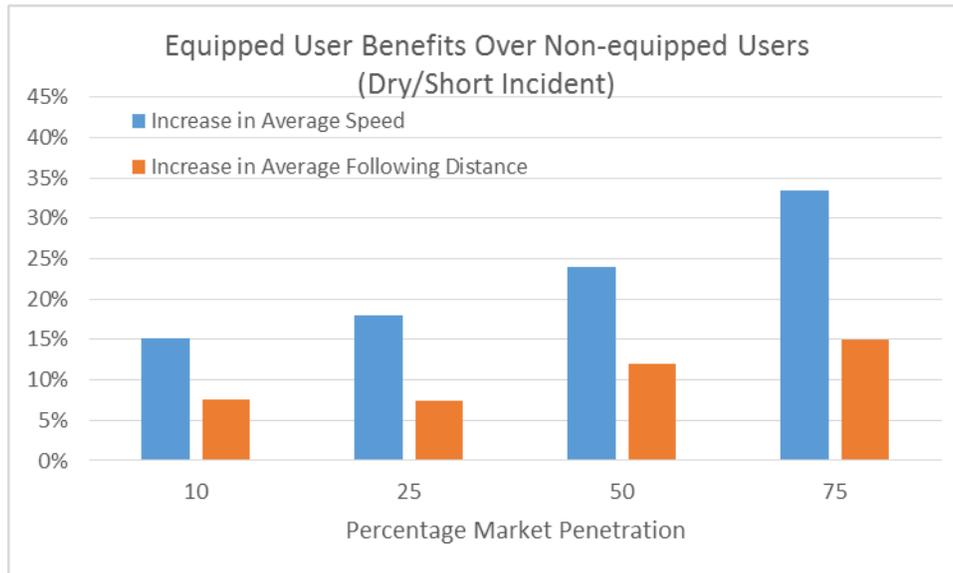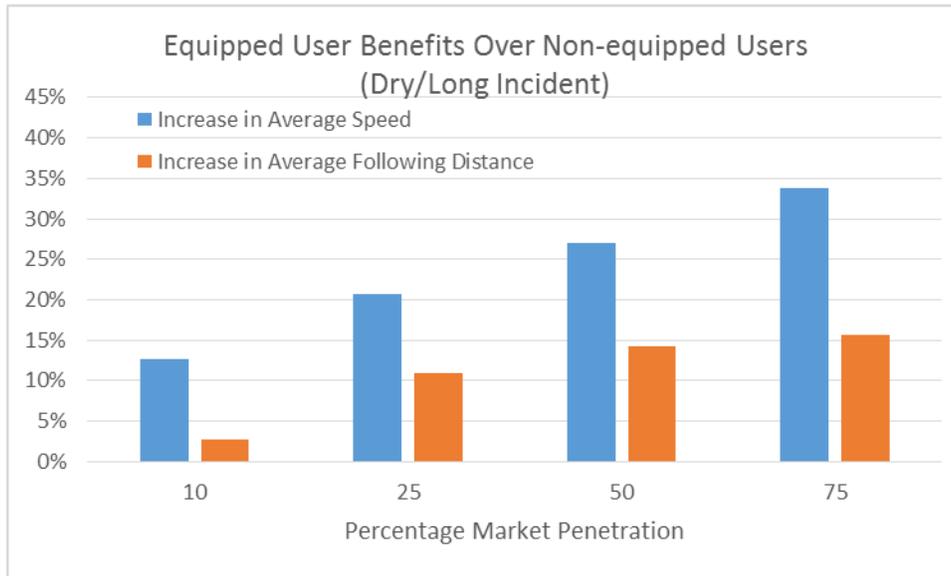

Source: Booz Allen Hamilton

Figure 4-15. User Benefits for Dry/Short Incident Case

4.4.1.2 Long Incident Duration

Figure 4-16 shows the user-benefits comparison between equipped and non-equipped vehicles when the incident duration is long (60 minutes). The trend of performance measures remains similar to the short incident case; however, the average benefits in terms of percentage difference from the non-equipped vehicles is slightly lower for the long incident case. The improvement in average speed for equipped vehicles when compared to non-equipped vehicles is an increasing function between 13 percent and 34 percent for rising market penetration between 10 percent and 75 percent.

At 10-percent market penetration, the increase in average following distance of equipped vehicles is 3 percent more than non-equipped vehicles. This steadily increases to 16 percent as market penetration reaches 75 percent. As described before, the following distance of vehicles is a direct safety indicator. A higher following distance indicates that vehicles have more time to respond to speed changes by the lead vehicle, thereby having lower maximum deceleration and lower probability of secondary crashes.

As in the previous case, the gap in benefits of equipped vehicles versus non-equipped vehicles expands as market penetration increases. Visual audits were done to detect this behavior. When the number of equipped vehicles increased, the non-equipped vehicles changed their behavior to act against the INC-ZONE recommendations. For example, as the market penetration increased, more vehicles started optimizing their trajectory to traverse the incident, which resulted in non-equipped vehicles moving farther from the optimal path, thereby being on closed lanes and lanes closest to the incident.

Source: Booz Allen Hamilton

Figure 4-16. User Benefits for Dry/Long Incident Case

4.4.2. Rainy Conditions

A similar analysis was done for the network that is calibrated for rainy conditions for both short and long incident durations. The results are discussed below.

4.4.2.1 Short Incident Duration

Figure 4-17 shows a comparison of the benefits achieved by road users equipped with the INC-ZONE system as compared to those who are not equipped, under rainy conditions with a short incident. As described earlier, these performance measures were collected within a 1-mile zone of the incident for the total duration of the incident to explicitly demonstrate the results. Similar to dry conditions, the difference in performance measures between equipped and non-equipped users increases with rising market penetration. However, the increase in performance measures due to the increase in market penetration is not as steep as in the dry weather conditions. This is due to the fact that under rainy conditions, the non-equipped vehicles are less likely to make lane-change decisions that could otherwise impact their performance.

In terms of the increase in average speed, the equipped vehicles have around 25 percent to 40 percent improvement over non-equipped vehicles. Increase in average following distance, an indirect safety measure, follows a similar trend, but the slope of change across different levels of market

penetration is less. The values fall between 14 percent and 19 percent. This is because, under rainy conditions, the average following distance is higher even for non-equipped vehicles due to visibility and braking restrictions.
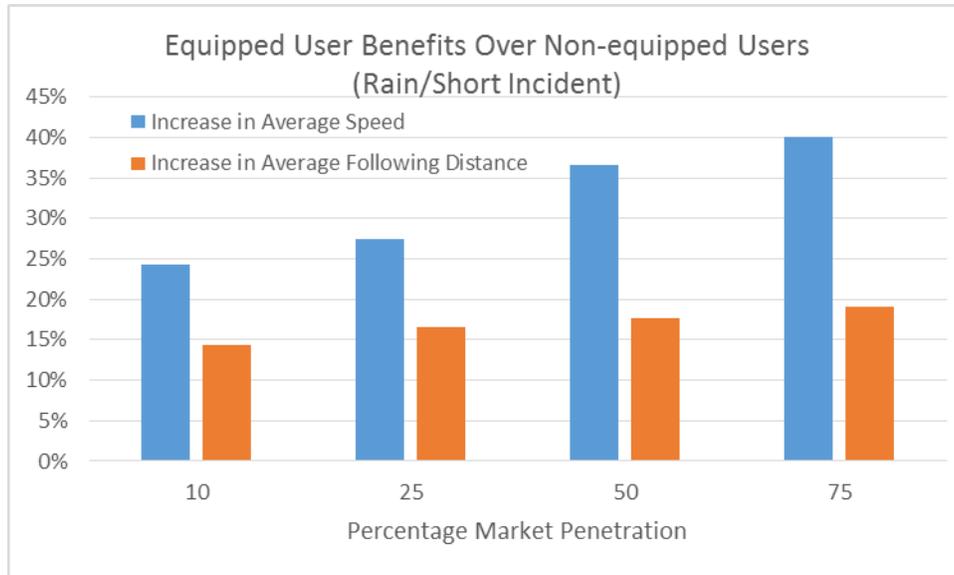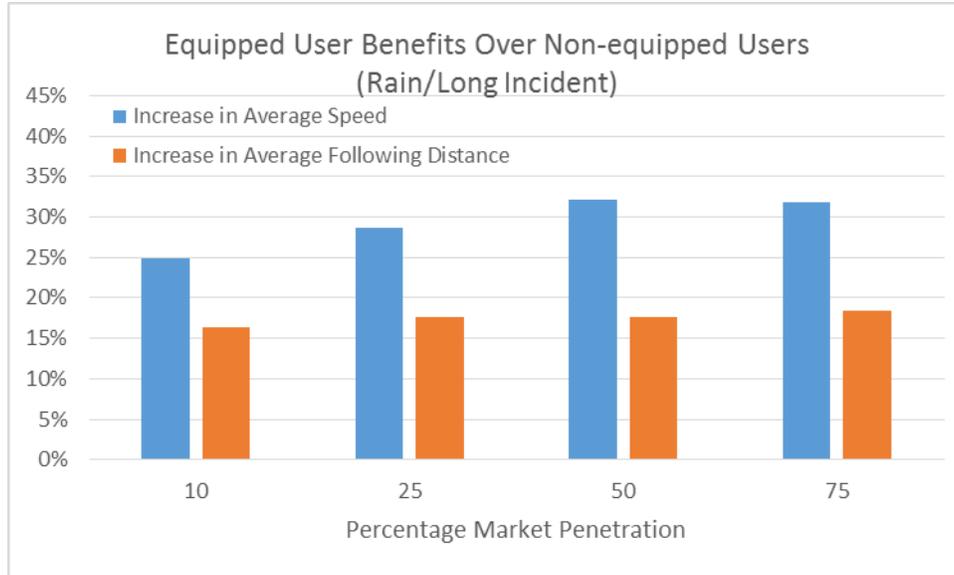
Figure 4-17. User Benefits for Rain/Short Incident Case

4.4.2.2 Long Incident Duration

Figure 4-18 demonstrates the three aforementioned performance measures for a rainy network with a long incident. The increase in average speed of equipped vehicles over non-equipped vehicles rises from 25 percent to 32 percent as market penetration grows. The increase in average following distance, like in the short incident case, showed minimal difference between varying levels of market penetration. The values varied between 16 percent and 18.5 percent.
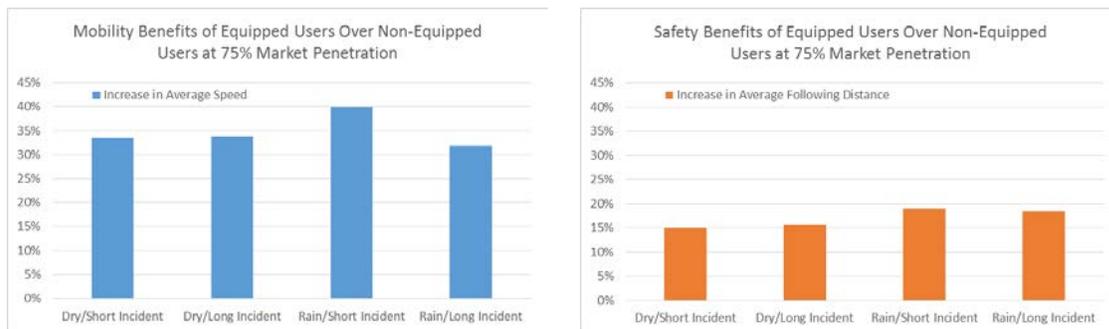
Source: Booz Allen Hamilton

Figure 4-18. User Benefits for Rain/Long Incident Case

4.4.3. Sensitivity to Operational Conditions

Figure 4-19 shows the performance of equipped vehicles over that of non-equipped vehicles under the four different operational conditions for 75-percent market penetration. On average, rainy conditions showed wider differences between equipped and non-equipped vehicles than dry conditions. For dry conditions, the increase in average speed of vehicles remains almost the same despite incident duration. This trend is not seen in rainy conditions, for which the benefits in terms of increase in average speed were 40 percent for short incident and 32 percent for long incident. Visual audits during the simulation suggested that the longer incident caused longer backup of vehicles due to the driver behavior characteristics set for rainy conditions. The increase in following distance, however, is almost the same for both incident lengths, but higher for rainy conditions.
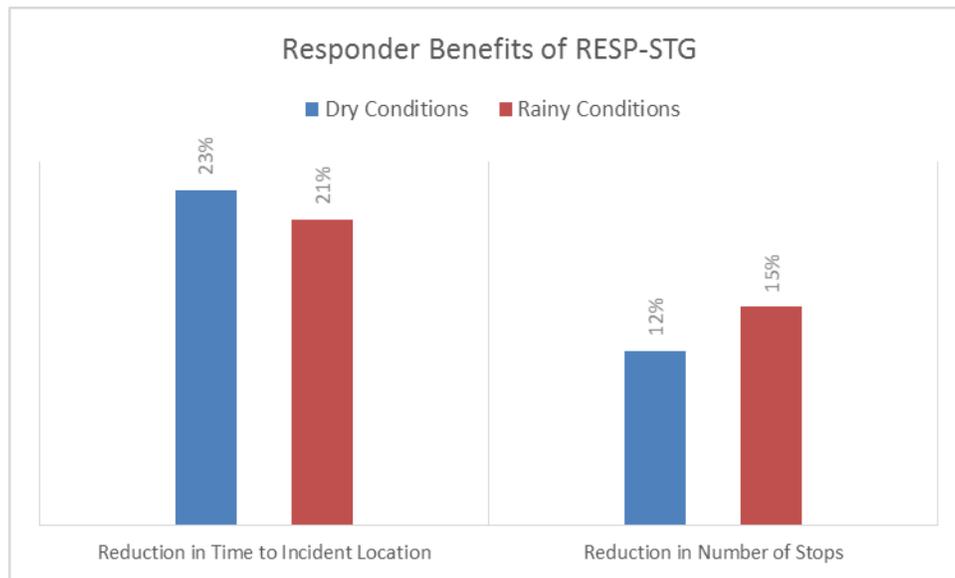

Source: Booz Allen Hamilton

Figure 4-19. Mobility and Safety Benefits of Equipped Users over Non-Equipped Users under Different Operational Conditions at 75-Percent Market Penetration

4.4.4. RESP-STG Specific Impacts

Figure 4-20 shows the performance improvement by emergency response vehicles that used the RESP-STG application for dry and rainy conditions. Note that the incident duration had no effect on the performance of emergency response vehicles since they were deployed after the onset of the incident. This analysis does not account for redeployment of emergency vehicles. RESP-STG-specific impacts used the routing and staging functionalities to simulate emergency response at the onset of incidents. Responder vehicle records were used to compute specific metrics studied in this report.

As shown in the figure, there is a significant reduction in the emergency vehicle's travel time to the incident location. This reduction is of the order of 23 percent to 21 percent for dry and rainy conditions, respectively. As far as the number of stops is concerned, a 12-percent (dry condtions) to 15-percent (rainy conditions) reduction is found when RESP-STG is used. Unlike the reduction in travel time, the reduction in number of stops is more for rainy conditions than for dry conditions. This is primarily due to the fact that when RESP-STG is not used, the emergency vehicle is subject to a higher number of stops under rainy conditions, which tends to increase the relative value.

Source: Booz Allen Hamilton

Figure 4-20. Mobility Benefits to Emergency Response Vehicles Due to the RESP-STG Application

Chapter 5. Findings and Impact Assessment

This chapter presents the findings and assessment of the potential impacts of INC-ZONE and RESP-STG under various conditions.

5.1. Limitations of Analysis

While the descriptions of the applications, as detailed in the system design document[6], can be implemented in real-world scenarios with some investment in technology and infrastructure, some of these functionalities cannot be modeled within a simulation environment. Traffic simulation software, for the most part, considers individual vehicles as agents and not individual people—travelers, responders, police officers, or workers. Therefore, for the modeling and simulation-based impact assessment, individual vehicle behavior is used and modified to replicate most of the application functionalities, rather than individual person behavior. For example, the INC-ZONE application includes a functionality that creates audible threat alerts about an errant vehicle for the safety of personnel on scene. Such functionalities cannot be modeled. Additionally, warnings and alerts to drivers to change lanes or slow down were issued as a vehicle command to achieve a desired lane and speed. Based on the built-in functions for compliance rates, the vehicles would choose to accept or decline this command.

Another assumption made in this study was combining the compliance rate with market penetration. The values demonstrated as market penetration in the results are a combination of both values since in a vehicle-based environment it is not easily possible to model vehicles that are connected, but do not comply with the vehicle commands. For example, a 50-percent market penetration with a 50-percent compliance rate is similar to a 25-percent market penetration with 100-percent compliance rate.

The database size to conduct a trajectory-based safety analysis was tremendous given that the network is massive and the simulation timeline is 5 hours (excluding warm-up and cool-down periods). Current trajectory-based safety analysis tools including SSAM (Surrogate Safety Assessment Model) cannot load files of this size. Therefore, the safety analysis was constrained to trajectories generated only in the incident time window, and for the 0.5-mile sublink that contains the incident.

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[6] *R.E.S.C.U.M.E. Prototype System Design Document*, Battelle, March 7, 2014

5.2. Extrapolation of Results

In addition to the network-wide impacts of INC-ZONE and RESP-STG, this impact assessment conducted an extended analysis where consolidated incident records on a road network in Maryland were used to generate quantifiable impacts of these applications on mobility across the network.

5.2.1. Scope of the Analysis

The analysis was carried out from January 1, 2014, to January 1, 2015, for the I-495 road network in Maryland. The incident data and the travel time data for the analysis were obtained from the Regional Integrated Transportation Information System (RITIS). A total of 6,921 incidents were used for the analysis. The analysis used the archived travel times from the RITIS I-495 data to generate metrics like travel time savings and monetized savings.

Figure 5-1. I-495 Maryland

Source: Squiggygfm - Own work. Licensed under Public Domain via Wikimedia Commons, accessed on 04/09/15,
http://commons.wikimedia.org/wiki/File:Capital_Beltway_Map_Color.svg#/media/File:Capital_Beltway_Map_Color.svg

Figure 5-1 shows the I-495 network that is part of the state of Maryland. The blue portion of the map shows Maryland and the I-495 route is marked in red. The length of I-495 in Maryland is approximately 41 miles.

5.2.2. Assumptions

The following assumptions were made:

1. The RITIS has archived travel time data from detectors that are installed across the I-495 network in Maryland. The travel times and volumes on I-495 are generated using the detector data from January 1, 2014, to January 31, 2014. These are used as representative values for the entire analysis.

2. The I-495 road network is assumed to have an average of three lanes.
3. Each incident zone is assumed to be a half-mile in length.
4. The percentage changes in sublink speed that are observed in the incident zones in the simulation study (Chapter 4) are used to compute travel time savings.
5. The value of time is assumed to be one-third to one-half of the average hourly wages (i.e., $15/hour in this study) [1].
6. The number of rainy days per year is assumed to be equivalent to 32.5 percent of the days in Maryland for the year 2014 [2].

5.2.3. RITIS Data

The travel time data came from the detectors installed on I-495 whose archived data can be accessed using the RITIS detector tools (see Figure 5-2). For the I-495 road network, data from 37 detectors was used. The data elements of interest are date, time location, speed, and volume.
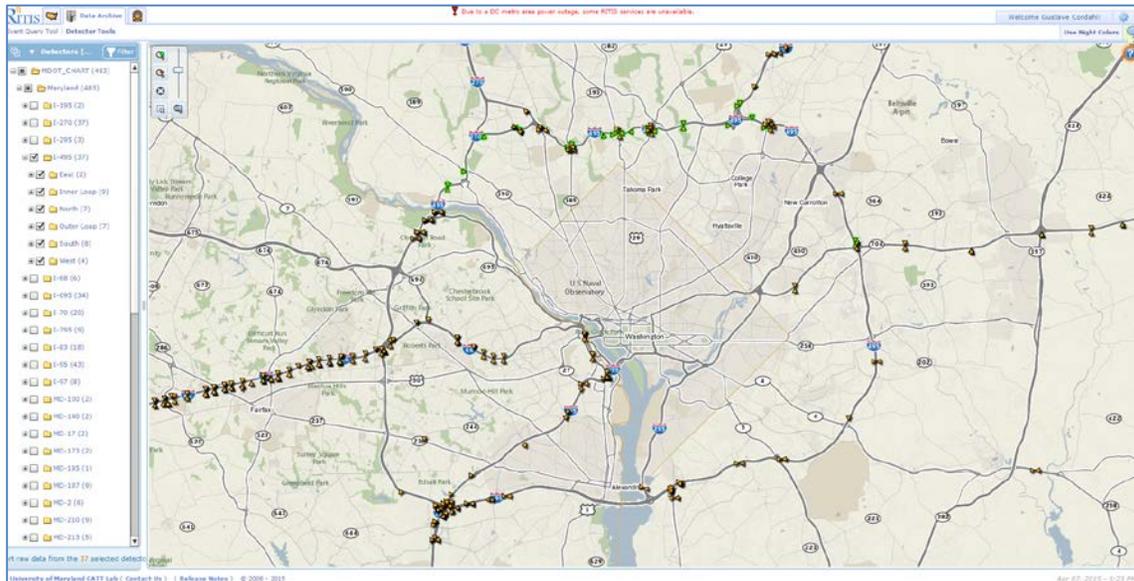
Source: RITIS, accessed April 2015

Figure 5-2. RITIS Detector Tools (the entire I-495 is shown, but data was used only from I-495 in Maryland)
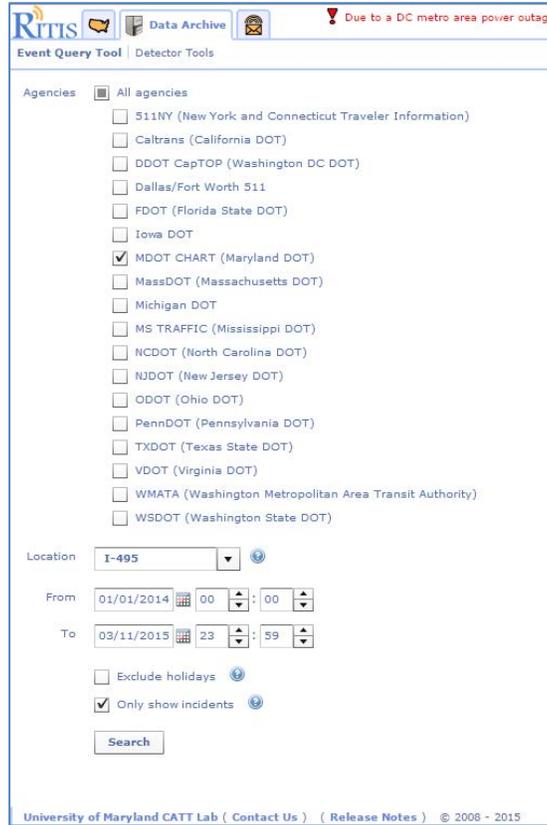
Source: RITIS, accessed April 2015

Figure 5-3. Event Query Tool on the RITIS Website

The incident data are obtained using the Event Query Tool hosted on the RITIS website (see Figure 5-3). The incident data were imported into Microsoft Excel for the analysis. Data elements used for the analysis are:

- Road
- Time Opened
- Duration
- Max. Lanes Closed.

5.2.4. Methodology and Results

The baseline used was the travel time and volume data obtained from RITIS. Table 5-1 presents the consolidated data that was used for analysis. The values were generated using the January 2014 detector data from RITIS.

Table 5-1. Average Speeds and Volumes for Each Day of the Week on I-495 from January 2014

Weekday	Avg Speed (mph)	Avg Volume (5min)	Avg Volume/Hr/Ln
Monday	60.27322	78.17502	938.1002
Tuesday	61.26496	64.58622	775.0346

Weekday	Avg Speed (mph)	Avg Volume (5min)	Avg Volume/Hr/Ln
Wednesday	60.41084	68.31086	819.7303
Thursday	59.43439	85.57294	1026.875
Friday	59.3164	83.21067	998.528
Saturday	60.20694	71.81471	861.7765
Sunday	66.96521	44.79741	537.5689

Source: Booz Allen Hamilton, April 2015

The incident data was cleaned by removing missing or incomplete entries. Cleaned data for 6,921 incident entries were used. The incident zone speed was calculated using the baseline speeds obtained from the detectors and multiplying them with the percentage decrease in sublink speeds observed in the simulations between scenarios without an incident and scenarios with an incident. An average decrease of 14.7 percent in the sublink speed was observed.

With the baseline incident zone speeds generated for each incident, the number of vehicles affected by the reduction in speed was computed. This was calculated using the travel time increase due to the incident in the incident zone (0.5 miles) and the number of vehicles passing the incident zone (i.e., the traffic volume). The results showed that a total of 175,938 vehicle hours were wasted due to incidents on I-495 between January 2014 and January 2015. The monetary value of this was estimated to be $2,639,069.07.

Once the baseline was established, the simulation results (percent changes in sublink speed and volume with the deployment of INC-ZONE) were used to calculate the benefits in terms of travel time savings for dry and wet conditions for different levels of penetration rate or market penetration (10 percent, 25 percent, 50 percent, 75 percent, and 100 percent). The corresponding results are presented below. The incidents were classified into bins such as less than 15 minutes, 15 to 30 minutes, 30 to 60 minutes, and over an hour.
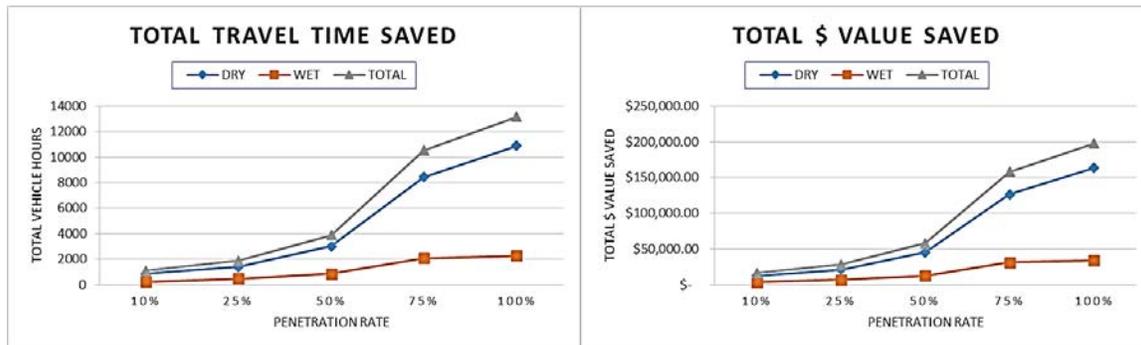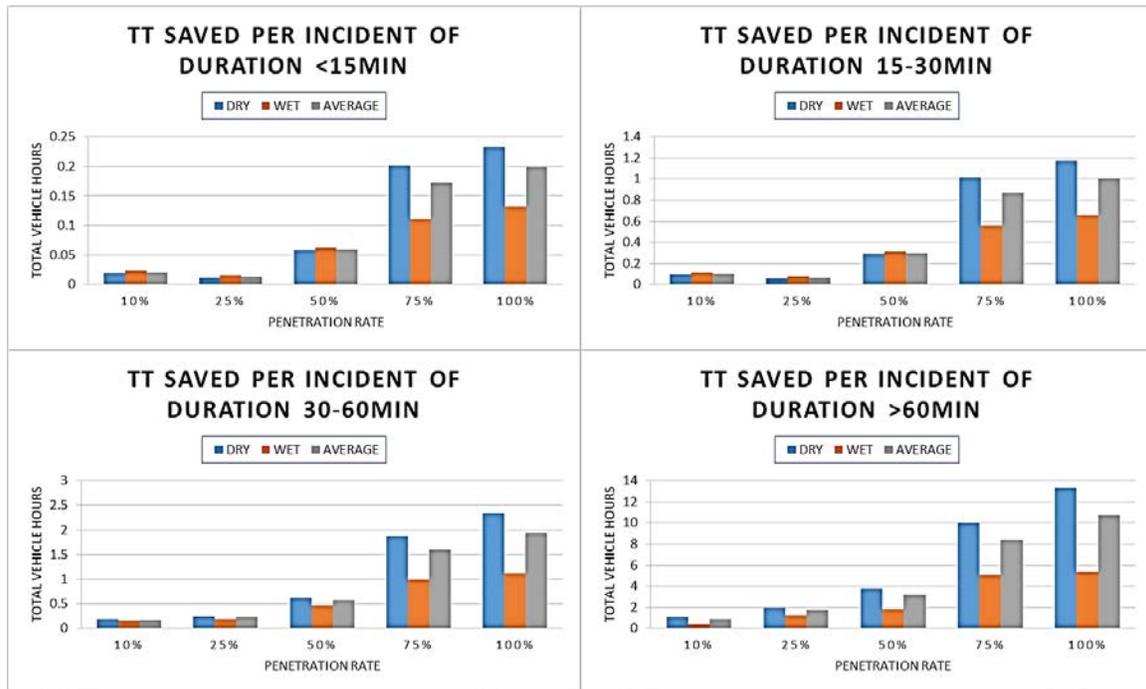

Source: Booz Allen Hamilton, April 2015

Figure 5-4. Travel Time and Monetary Benefits of INC-ZONE with Different Market Penetration Rates

Figure 5-4 shows that the benefits of INC-ZONE increase with rising market penetration rates for both dry and rainy/wet scenarios. The benefits observed for the dry conditions are higher than those for rainy conditions (mostly because there were more dry days than days with precipitation). This is due to the fact that the lane-changing behavior is not affected by inclement weather in dry conditions. The vehicles can use the information provided by the INC-ZONE application and change lanes before approaching the incident zones. The total values are only based on travel time estimates and not

other benefits like reduced fuel consumption or increased safety. The results are also annual estimates for approximately 41 miles of I-495 in Maryland.

Source: Booz Allen Hamilton, April 2015

Figure 5-5. Travel Time Savings Per Incident for Different Incident Durations with the Deployment of INC-ZONE at Varying Penetration Levels

Figure 5-5 shows the computed travel time savings per incident for the vehicles passing through the incident zone for the duration of the event. The benefits are measured by the total vehicle hours that are saved by all vehicles passing through an incident zone during the duration of the incident. The savings are proportionate with the duration of the incidents.

The graphs shown in Figure 5-5 have different scales on the y-axis. The benefits increase with rising penetration rates for all incident durations. The benefits for the rainy conditions are less than those for the dry conditions. This can be explained by the ease of compliance with INC-ZONE during dry conditions as compared to rainy conditions and the fact that vehicles may already be traveling at lower speeds during rainy conditions. The benefits tend to be higher for incidents of longer durations because the number of vehicles affected by the incident are higher as compared to incidents of shorter durations. Although individual vehicle travel time savings may be lower for longer incidents, the total travel time savings for all the vehicles passing through the longer incident zones are higher.

5.3. Conclusions

The qualitative assessment of INC-ZONE and RESP-STG, which is based on the interviews of demonstration participants, highlights the potential benefits of the two R.E.S.C.U.M.E. applications. The majority of participants recognized the potential safety and mobility benefits of these applications once they become widely implemented. Reduction in total response time, queued delay, and

clearance time are some of the mobility benefits, and reduction in secondary incidents with a focus on responder injuries is an example of safety benefits recognized by the participants. Most participants think that agencies will be receptive to the use of these applications, especially the enforcement and emergency response agencies. As the R.E.S.C.U.M.E. applications become more widely adopted, it will be easier to integrate them with the existing systems.

The corridor modeling and simulation of the INC-ZONE and RESP-STG applications revealed important conclusions regarding the effectiveness of these applications under test conditions. The following are the major conclusions.

Network-wide Performance:

1. The average network-wide reduction in delay and increase in speed was higher for dry conditions than rainy conditions. The percent benefit was greater for average delay than for average speed.
2. The reduction in network delay was between 1 percent and 14 percent, and the increase in average speed was between 1 percent and 8 percent for dry conditions. These benefits were more for long incident than short incident scenarios.
3. The reduction in network delay was between 1 percent and 7 percent, and the increase in average speed was between 0.25 percent and 3 percent for rainy conditions. These benefits were more for short incident than long incident scenarios.
4. There is a considerable increase in delay reductions and speed improvement as clearance times are reduced using the RESP-STG application. Network-wide delay reductions were up to 3.25 percent given a 15-percent reduction in clearance times under dry conditions.

Incident-zone Level Performance:

1. In terms of mobility, the increase in section throughput increases with market penetration, with values ranging between 1 percent and 14 percent.
2. Mobility improvement at the incident zone, as reflected by the increase in section throughput, was found to be higher under dry conditions than rainy conditions for all levels of market penetration. The average improvement under dry conditions was around 2 percent higher than under rainy conditions.
3. Safety metrics studied were reduction in maximum deceleration and reduction in sublink speed. Use of INC-ZONE in dry conditions resulted in more improvement than in rainy conditions.
4. Reduction in maximum deceleration was found to be between 1 and 89 percent for different operational conditions, with the highest improvement being for the dry conditions with long incident case.
5. Reduction in sublink speed ranged between 0 and 14 percent with the highest reduction for the dry conditions with long incident case.

User-level Benefits:

1. For INC-ZONE, the increase in average speed and average following distances for equipped users versus non-equipped users were studied. Use of INC-ZONE in rainy conditions with short incidents showed more user benefits than for other operational conditions.

2. The increase in average speed for INC-ZONE users was between 13 percent and 40 percent over non-users.
3. The increase in average following distance for INC-ZONE users was between 2.5 percent to 19 percent over non-users.
4. The difference between average speed and average following distance of users and non-users of INC-ZONE increased with rising market penetration.
5. Emergency vehicles showed improvement on the basis of reduction in travel time to the incident location and reduction in number of stops when RESP-STG was used.
6. The reduction in travel time of emergency vehicles was up to 23 percent and the reduction in number of stops was up to 15 percent.

An extrapolation of results from the simulation of INC-ZONE using real-world incident data revealed that the anticipated benefits of INC-ZONE are significant. The benefits range from a few minutes to almost an hour of travel time savings for each incident on I-495 with just 10-percent deployment of INC-ZONE, indicating the potential benefits in the short term with low deployment and penetration of INC-ZONE. The benefits increase steadily with rising market penetration of INC-ZONE. The travel time savings are higher for incidents of longer durations and for incidents occurring when the conditions are dry. Although mobility benefits were assessed in the extrapolation of results, other benefits like reduced fuel consumption, reduced emissions, or improved safety could result in additional cumulative benefits.

Future research could be directed to study the compliance of drivers with the information provided by INC-ZONE. Without driver compliance, the benefits could reduce drastically. Another potential area of research is the impact of deploying INC-ZONE on a network with multiple incidents. The impacts of INC-ZONE on different facilities like freeways and arterials with different traffic demand levels could be studied. The interactions of the applications in the R.E.S.C.U.M.E. bundle need to be studied in further detail to fully understand the microscopic impacts of these applications when deployed together or with other connected vehicle applications.

Chapter 6. Appendix

6.1. VISSIM API

VISSIM software's COM capabilities are used to develop APIs pertaining to INC-ZONE and RESP-STG. This section highlights snippets of VISSIM COM functionalities that enable specific applications.

6.1.1. Initiating Incident

An incident is initiated dynamically by adding a stopped vehicle to the network at a given time and location. The snippet for doing this is given below:

```
Vissim.Net.Vehicles.AddVehicleAtLinkPosition(CrashType,CrashLink,CrashLane
        ,CrashLoc,DesiredSpeed,InteractionType)
```

6.1.2. Threat Determination

Threat determination to find out which vehicles are within the incident zone is done every time-step by querying multiple attributes of the vehicles. The snippet is given below:

```
Vissim.Net.Vehicles.GetMultipleAttributes(('No','Speed','Lane','DesSpeed',
        'Pos','DesLane','NextLink'))
```

6.1.3. Change in Speed and Lanes

Once vehicles in the incident zone are identified, their speeds and lanes are altered using the desired speed and desired lane attributes as given below:

```
Vissim.Net.Vehicles.ItemByKey(VehID).SetAttValue('DesSpeed',value)
Vissim.Net.Vehicles.ItemByKey(VehID).SetAttValue('DesLane',value)
```

However, the lane-change commands issued will last until another command is given. To ensure that its default lane-change behavior is achieved after crossing the incident, all lane changes are defaulted to the value "9999," which will allow vehicles to rely on their default lane-choosing behavior.

6.1.4. Deploying Emergency Vehicle

Emergency vehicles are deployed by adding a vehicle at the position of the fire station. Dynamic route guidance is provided to this vehicle so that its trip will end in the incident zone. The deployment uses a similar COM attribute as initiating the incident.

6.1.5. Detecting Ramp Congestion

When RESP-STG is modeled, the emergency vehicle is deployed and guided from the fire/EMS station that is shortest to the incident zone based on travel time. This requires identifying congestion on entry ramps that feed the freeway. A data collection measurement is used for this purpose using the code snippet as shown below:

```
Vissim.Net.DataCollectionMeasurements.ItemByKey(DCId).AttValue('Speed(Curr
      ent,Avg,All)')
```

6.2. Preliminary Analysis

Preliminary analysis was done with the overall simulation network under limited test conditions to determine the best combination of vehicle commands that will constitute effective INC-ZONE and RESP-STG applications.

6.2.1. INC-ZONE

Given that vehicle commands are used in the simulation of INC-ZONE rather than "alerts" or "advisories," specific characteristics of the commands can greatly influence the performance of the application. Preliminary analysis involves testing various *versions* of applications on a minimal network so that a comparison can be made on how vehicle commands could impact the overall network performance of the application. In the application modeled, three major types of commands are used by the INC-ZONE application:

1. Alteration of desired speed of vehicles
2. Alteration of desired lane to be taken by vehicles
3. Freezing all the lane changes near the incident location to enhance safety.

Three preliminary versions of INC-ZONE were developed with various sets of vehicle commands that will impact the performance measures.

1. Type 1 used only speed commands given through the connected vehicle framework. Lane tapering and lane merging was done in the traditional fashion based on the individual vehicle's lookahead distance. These commands were issued as per the distance guidelines corresponding to work-zone configuration tables given in the MUTCD.
2. Type 2 was developed with both speed commands and lane-change commands that will replicate the INC-ZONE system design. The lane-change commands, in this version, were based on the individual vehicle's distance from the incident zone. Once the vehicle is in the lane-change *alert* distance specified in the prototype (which is basically the sum of buffer length and taper length from MUTCD), the equipped vehicles that are in the incident lane will receive notification to change their desired lane.
3. Type 3 was developed with both speed commands and advanced lane-change commands. Advanced lane-change commands enable lane changes at advanced placement distance from the distance specified in Version 2. This distance corresponds to the lane-change *advisory* in the prototype.

These three versions were tested in the US 101 network for 2-hour simulations under dry conditions, to minimize run-time. Only network performance variables were compared in the preliminary analysis. A 15-minute incident that resulted in a single lane closure was simulated at the end of hour 1. Ten random-seed simulations were done for each case, and the incident location is the same as the incident location for overall analysis.

6.2.2. Comparison of Results

For the preliminary analysis, only network mobility measures were compared for the three types of INC-ZONE developed, so that a single type can be finalized as the overall INC-ZONE application for overall analysis. The three performance measures that were compared include:

1. **Average Vehicle Delay:** Vehicle delay is represented as the difference in travel time of the actual vehicle in simulation and the hypothetical travel time when the vehicle travels at free-flow speed over the entire modeled corridor. Average vehicle delay represents the overall delay in the network averaged over the number of vehicles in the network. The results are shown in Figure 6-1.
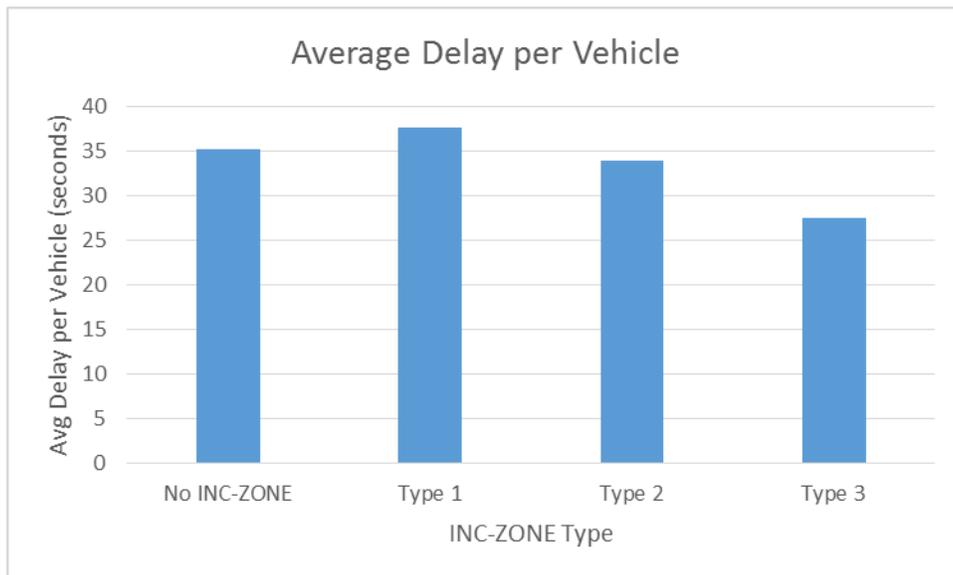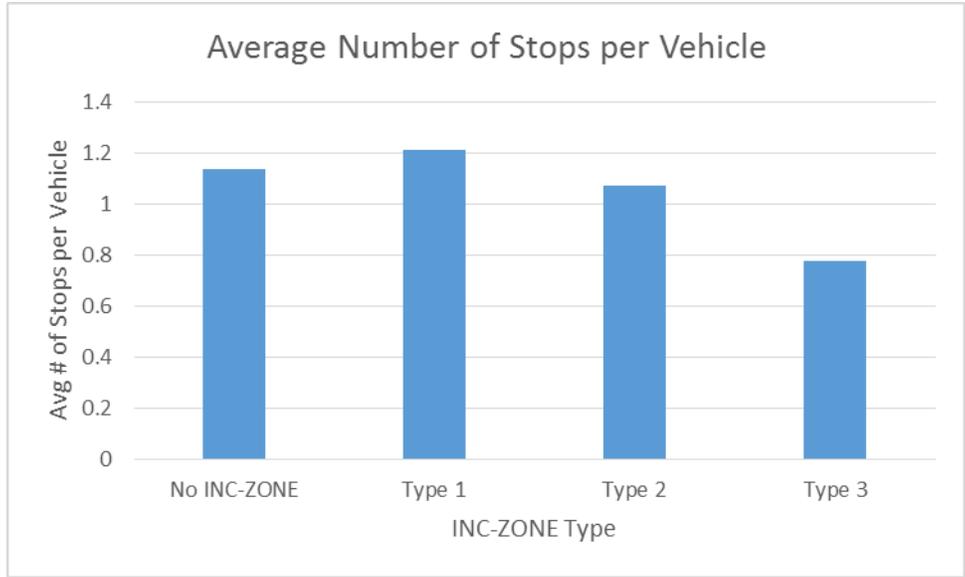

Source: Booz Allen Hamilton

Figure 6-1. Average Vehicle Delay for Preliminary Analysis

The figure shows that mobility benefits in terms of delay will come only after introducing lane-change commands. Type 1 showed 7 percent more delay when compared to the "No INC-ZONE" case. However, Types 2 and 3 showed 3-percent and 22-percent reduction in average delay.

2. **Average Number of Stops:** In this metric, the number of stops in the overall network simulation is averaged over the number of vehicles simulated and is an indirect metric of safety. The results are shown in Figure 6-2.
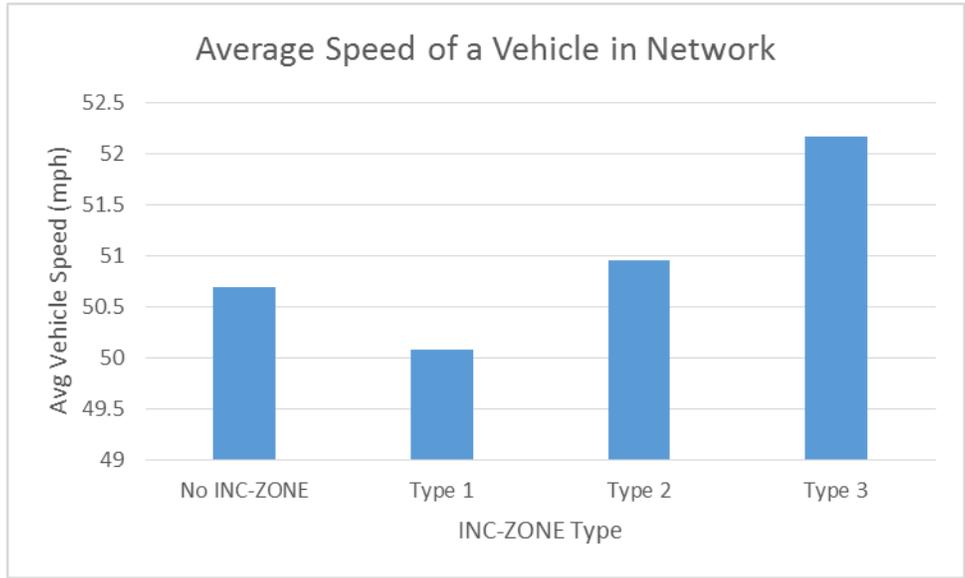
Source: Booz Allen Hamilton

Figure 6-2. Average Number of Stops for Preliminary Analysis

The figure shows that Type 1 adds 7-percent stops to an average vehicle when compared to the "do-nothing" case, while Types 2 and 3 reduces the average number of stops by 6 percent and 32 percent respectively.

3. **Average Speed:** This metric represents the average travel speed of a vehicle in the network. The free-flow speed of the highway is considered to be 65 miles per hour. The results are shown in Figure 6-3.

Source: Booz Allen Hamilton

Figure 6-3. Average Vehicle Speed in the Network for Preliminary Analysis

A higher average speed represents better mobility in the network. Among the three types of INC-ZONE applications compared, Type 1 reduced the average vehicle speed by 1 percent. Types 2 and 3 increased the average vehicle speed by 1 percent and 3 percent respectively.

The above analysis shows that Type 3 provides the maximum benefit in terms of mobility and indirect safety benefits. This is primarily due to the fact that providing early lane changes can reduce congestion near the bottleneck. In addition, the incident location simulated is halfway between an entrance ramp and an exit ramp. The early lane changes on the mainline provide enough room for entering vehicles to traverse the incident zone smoothly, while with Types 1 and 2, the entrance ramp was queued because of the incident zone.

6.2.3. RESP-STG

Responder vehicles were modeled using an HGV type vehicle to represent a fire truck or an ambulance of similar acceleration and maneuverability. HGV is a default vehicle type in VISSIM and represents Heavy Goods Vehicles.

In the base case when no RESP-STG is used, the responder vehicles are deployed after a defined time beyond the start of the incident. This time is a representative of three variables:

1. Time taken for incident detection
2. Time taken for incident verification
3. Time taken for response dispatch.

Figure 6-4 shows this timeline set-up.
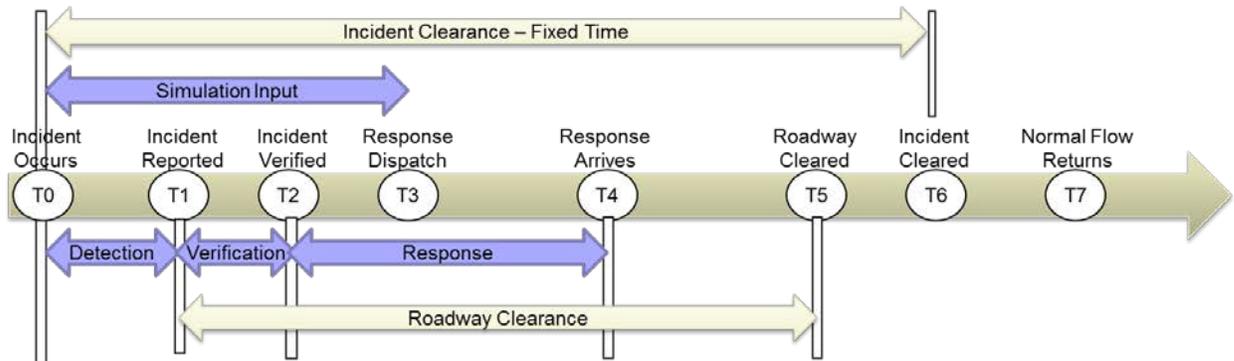
Source: Booz Allen Hamilton

Figure 6-4. Responder Dispatch Timeline

Once the responder is dispatched from the closest fire/EMS station, the responder vehicle is routed to the incident location and staged near the incident. The responder vehicle behavior is chosen as the default behavior during its course.

For the test cases with RESP-STG modeling, the responder vehicles are deployed in a similar method, but use two data-sets to modify en route behavior:

1. **Routing Decision:** The routing decision involves which ramp to take to reach the incident location and is made based on data on average ramp speeds collected using Data Collection Measurements.

2. **Staging Decision:** The staging decision is made based on whether the incident lane is followed by a backlog of vehicles. The average queued data from vehicle records is used to make this judgment.

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