Analysis, Modeling, and Simulation (AMS) Testbed Development and Evaluation to Support Dynamic Mobility Applications (DMA) and Active Transportation and Demand Management (ATDM) Programs

Evaluation Report for DMA Program

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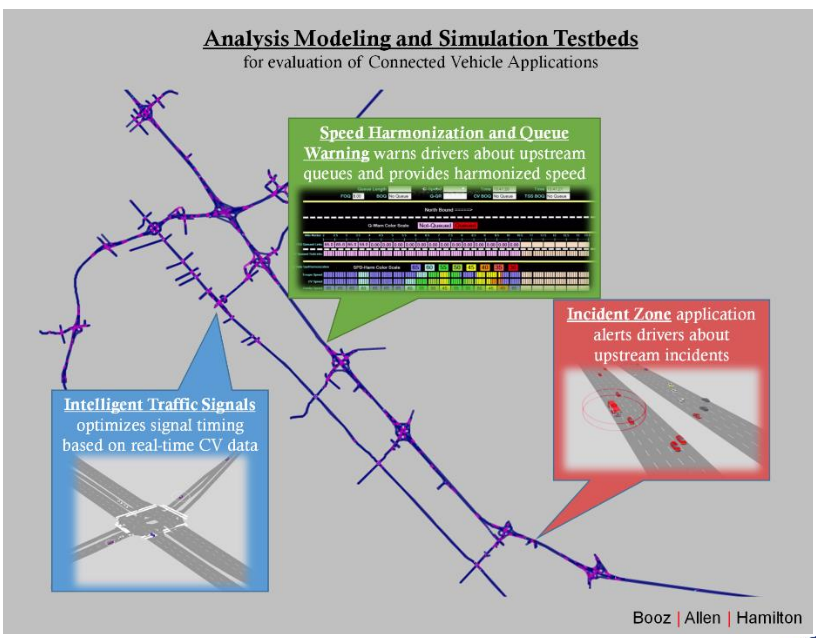

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16. Abstract

The primary objective of this project is to develop multiple simulation testbeds/transportation models to evaluate the impacts of DMA connected vehicle applications and the active and dynamic transportation management (ATDM) strategies. The outputs (modeling results) from this project will help USDOT prioritize their investment decisions for DMA and ATDM programs.

While the project aims at evaluating both DMA applications and ATDM strategies, the primary purpose of this report is to document the evaluation done in terms of DMA applications using the AMS testbeds. ATDM evaluation will be documented in a separate report. Primarily, San Mateo and Phoenix were used as DMA-centric testbeds and were used to assess the DMA applications under various scenarios of combinations of applications, communication attributes and evaluation attributes to answer a set of research questions set forth by the USDOT.

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Executive Summary

The United States Department of Transportation (USDOT) initiated the Active Transportation and Demand Management (ATDM) and the Dynamic Mobility Applications (DMA) programs to achieve transformative mobility, safety, and environmental benefits through enhanced, performance-driven operational practices in surface transportation systems management. In order to explore a potential transformation in the transportation system's performance, both programs require an analysis, modeling, and simulation (AMS) capability. As part of this project, the team developed six AMS testbeds to evaluate these DMA applications and ATDM strategies using real-world operational conditions. They are the San Mateo (CA), Pasadena (CA), Dallas (TX), Phoenix (AZ), Chicago (IL), and San Diego (CA) testbeds.

While the project aims to evaluate both DMA applications and ATDM strategies, the primary purpose of this report is to document the evaluation of DMA applications using the AMS testbeds. ATDM evaluation will be documented in a separate report. Primarily, San Mateo and Phoenix were used as DMA-centric testbeds to assess DMA applications under various scenarios, testing different combinations of applications, communication attributes, and evaluation attributes to answer a set of research questions set forth by the USDOT. Through these research questions, the report is expected to provide additional insights to readers on the different DMA applications and how they can be implemented and evaluated in a model-based simulation environment. It will also discuss the trade-off and impact of providing connected vehicle and legacy system data to the applications; synergies and conflicts between the applications; and favorable operational conditions, modes, and facility types for the applications. The report will provide an evaluation of their deployment readiness in terms of data availability, infrastructure requirements, maturity, and deployment schedule. Additionally, the report evaluates these applications based on the messaging protocols and communication technology (including latency, range, and error rates) that supports the applications.

DMA Applications

Specifically, this evaluation includes six bundles of applications. Some of the applications are prototyped together through two simulation-based testbeds. The six bundles are pictured in Figure ES-1.

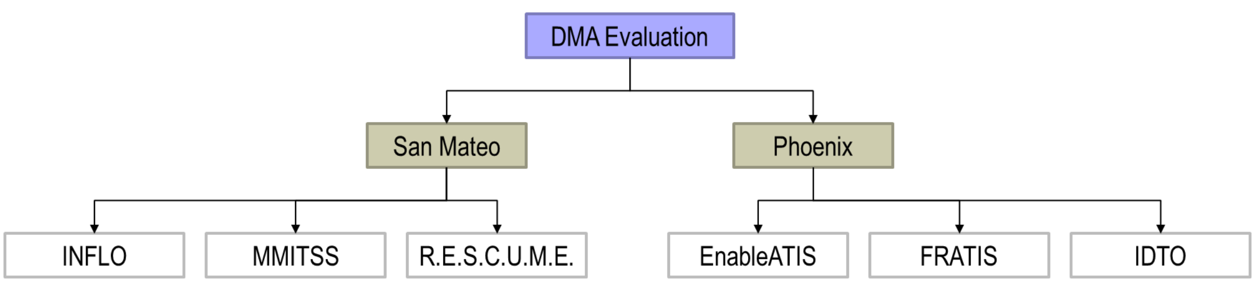

Figure ES-1: Application Bundles [Source: Booz Allen]

They application bundles are:

1. INFLO – Intelligent Network Flow Optimization
    a. Q-WARN – Queue Warning
    b. SPD-HARM – Dynamic Speed Harmonization
2. MMITSS – Multi-Modal Intelligent Traffic Signal Systems (I-SIG or Intelligent Signal Control application is assessed in this evaluation)
3. R.E.S.C.U.M.E. – Response, Emergency Staging and Communications, Uniform Management, and Evacuation.
    a. INC-ZONE - Incident Scene Work Zone Alerts for Drivers and Workers
    b. RESP-STG - Incident Scene Pre-Arrival Staging Guidance for Emergency Responders
4. EnableATIS – Enable Advanced Traveler Information Systems
5. IDTO – Integrated Dynamic Transit Operation
    a. T-DISP – Dynamic Transit Operations
    b. D-RIDE – Dynamic Ridesharing
6. FRATIS – Freight Advanced Traveler Information Systems
    a. F-ATIS – Freight Real-Time Traveler Information with Performance Monitoring
    b. F-DRG – Freight Dynamic Route Guidance

IDTO also includes the T-CONNECT application, which aims to improve rider satisfaction and reduce expected trip time for multimodal travelers by protecting transfers between both transit and non-transit modes and facilitating coordination between multiple agencies. The prototyped T-CONNECT application requires assigning passengers to vehicles (including transit vehicles) in the simulation model and holding buses and transit vehicles so that a passenger can make a connection after a request to hold is acknowledged and accepted. This requires significant additional features that are not available in current simulation testbeds. Currently in the Phoenix testbed, passengers/people only appear in the decision-making activity of selecting a start time and a route. After choosing a start time and route, the simulated entity is a vehicle with a given number of passengers. Due to this limitation, the T-CONNECT application was not evaluated in this project.

The applications are classified into tactical and strategic applications.[1] Tactical applications focus on influencing decisions and maneuvers made by system users (e.g., drivers) to pre-position or control their vehicles while en-route. Tactical applications also include applications that influence control/advisory decisions generated by system managers to influence these short-term tactical behaviors/maneuvers. Bundles such as INFLO, MMITSS, and R.E.S.C.U.M.E are examples of tactical applications. Strategic applications primarily influence long-term decisions made by travelers in response to traffic conditions and travel experiences. Strategic applications also include applications that emulate control/advisory decisions made by system managers to influence these long-term travel choices. Applications such as EnableATIS, IDTO, and FRATIS are examples of strategic applications.

Testbed Summary

The AMS testbed project spans over six testbeds, namely – San Mateo, Phoenix, Dallas, Pasadena, Chicago, and San Diego. However, San Mateo and Phoenix were the primary DMA-specific testbeds and are used in this report.

[1] Wunderlich, Vasudevan and Sandelius, Analysis, Modeling, and Simulation (AMS) Testbed Requirements for Dynamic Mobility Applications (DMA) and Active Transportation and Demand Management (ATDM) Programs, Report No. FHWA-JPO-13-098 to USDOT ITS Joint Program Office.

The San Mateo testbed is an 8.5-mile-long stretch of the US-101 freeway and State Route 82 (El Camino Real) in San Mateo County, located approximately 10 miles south of the San Francisco International Airport (SFO). The corridor is bounded by the coast range on the west side and the San Francisco Bay on the east side. State Route 92 (with the San Mateo Bridge) is the only east-west connector in the corridor that extends beyond the physical boundaries of the corridor. SR-92 goes from the Pacific Coastline through the coast range and across the San Francisco Bay to Hayward on the east side of the bay. All north-south traffic on the west side of the bay is limited to the US-101 freeway, El Camino Real, and Interstate 280 (not included in the testbed). This testbed accounts for a non-holiday 5-hour afternoon peak period between 2:30 pm and 7:30 pm.

The Phoenix testbed covers the entire Maricopa Association of Governments (MAG), which is home to more than 1.5 million households and 4.2 million inhabitants. This multi-resolution simulation model considers multiple modes, such as single/high occupancy vehicles, transit buses, light-rail, and freight vehicles. The region covers an area of 9,200 square miles and is characterized by a low-density development pattern, with a population density of about 253 people per square mile. The region has one city with more than one million people (Phoenix) and eight cities/towns with more than 100,000 people each. The region has experienced dramatic population growth in the past two decades, with the pace of growth slowing rather significantly in 2008-2012 period in the wake of the economic downturn. The region is home to the nation's largest university (Arizona State University with more than 73,000 students), several special events centers and sports arenas, recreational opportunities, a 20-mile light rail line, and a large seasonal resident population. The Tempe area, which covers an area of 40 square miles, is the focus of the testbed. This testbed only considers afternoon peak traffic between 3:00 pm and 7:00 pm.

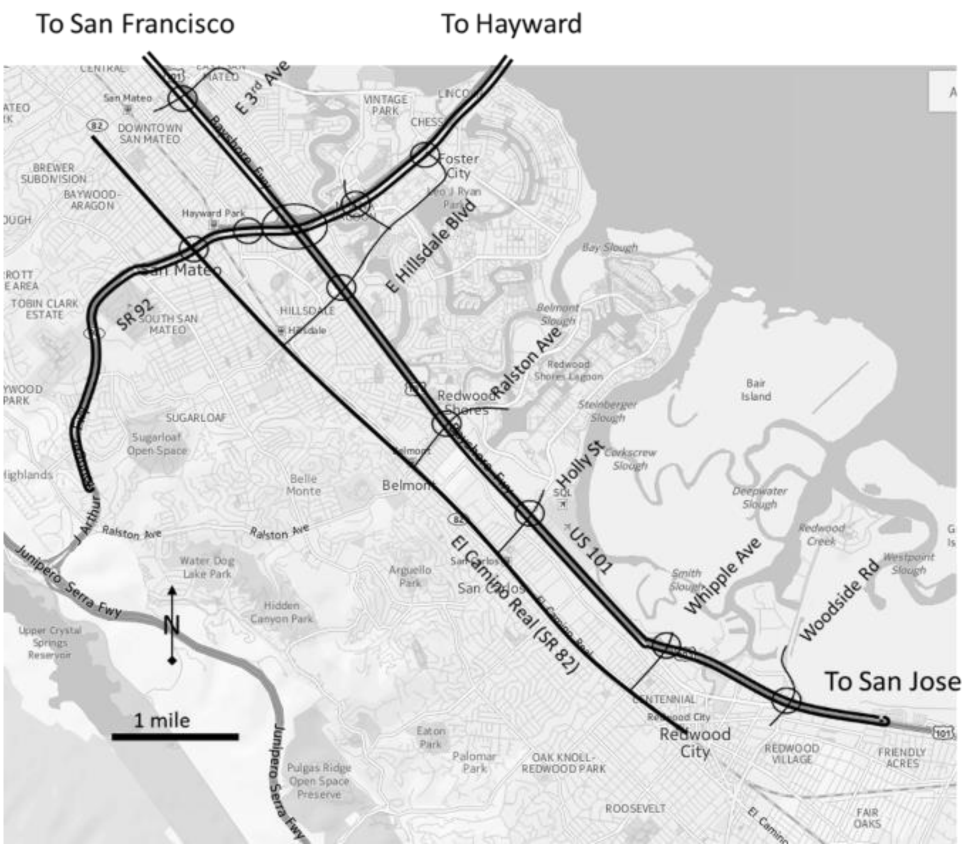

Figure ES-2: San Mateo Testbed Network [Source: Booz Allen]

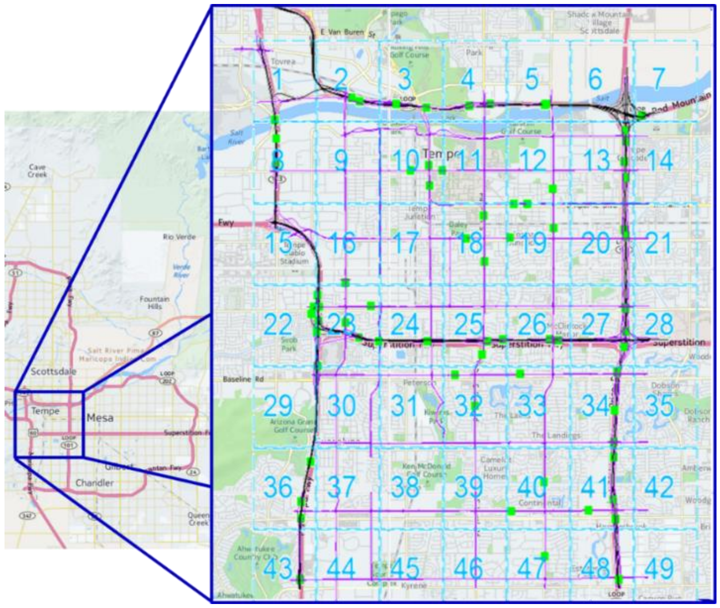

Figure ES-3: Phoenix Testbed Network [Source: Booz Allen]

Research Questions and Hypotheses

This evaluation is focused on a set of 29 research questions set forth by the USDOT. The team identified evaluation scenarios to help answer these questions and found 23 questions that can be answered using simulation-based qualitative and quantitative analysis. Significant efforts beyond the scope of this project would be required to answer the remaining questions. The Table ES-1 provides these research questions and their corresponding analysis hypotheses as identified in FHWA-JPO-13-097[2].

Table ES-1: DMA Research Questions and Hypotheses

ID	*DMA Research Question*	*Analysis Hypotheses*
1	Will DMA applications yield higher cost-effective gains in system efficiency and individual mobility, while reducing negative environmental impacts and safety risks, with wirelessly-connected vehicles, infrastructure, and travelers' mobile devices than with legacy systems? What is the marginal benefit if data from connected vehicle technology are augmented with data from legacy systems? What is the marginal benefit if data from legacy systems are augmented with data from connected vehicle technology?	Compared to legacy systems, DMA applications that make use of new forms of wirelessly-connected vehicle, infrastructure, and mobile device data will yield cost-effective gains in system efficiency and individual mobility, while reducing negative environmental impacts and safety risks.

[2] Vasudevan and Wunderlich, Analysis, Modeling, and Simulation (AMS) Testbed Preliminary Evaluation Plan for Dynamic Mobility Applications (DMA) Program, FHWA-JPO-13-097, November 2013, Accessed at http://ntl.bts.gov/lib/51000/51000/51006/2CF6ABEA.pdf

ID	DMA Research Question	Analysis Hypotheses
2	Are the DMA applications and bundles more beneficial when implemented in isolation or in combination?	Applications which act on different facility types are more likely to be synergetic. For example, INFLO works on freeways and MMITSS works on arterials. Together, they can improve overall mobility.
3	What DMA applications, bundles, or combinations of bundles complement or conflict with each other?	Applications which act on similar facility types and provide similar types of advisories to drivers are more likely to be conflicting. For example, INFLO and INC-ZONE acts on vehicles that are on a freeway through "speed recommendations". These could be conflicting.
4	Where can shared costs or cost-effective combinations be identified?	Bundles that works on the same facility type will have shared connected vehicle technology deployment costs.
5	What are the tradeoffs between deployment costs and benefits for specific DMA bundles and combinations of bundles?	Incremental increase in deployment will result in higher benefit-cost ratio up to a certain deployment cost threshold, after which benefit-cost ratio will reduce.
6	What DMA bundles or combinations of bundles yield the most benefits for specific operational conditions?	Certain DMA bundles or combinations of bundles will yield the highest benefits under specific operational conditions. For example, a combination of R.E.S.C.U.M.E and EnableATIS will have greater impact on days with high-demand and incidents than a combination of FRATIS and EnableATIS.
7	Under what operational conditions are specific bundles the most beneficial?	A DMA bundle will yield the highest benefits only under certain operational conditions. For example, on non-incident days, R.E.S.C.U.M.E. will have limited impact.
8	Under what operational conditions do particular combinations of DMA bundles conflict with each other?	Certain combinations of bundles will conflict with each other under specific operational conditions, resulting in no benefits or reduced benefits. For example, under high traffic, INC-ZONE application may not give any benefit since there is not much room for improvement.
9	Which DMA bundle or combinations of bundles will be most beneficial for certain modes and under what operational conditions?	Certain DMA bundles or combinations of bundles will yield the highest benefits for specific modes and under certain operational conditions. For example, FRATIS applications provide large benefits to freight vehicles.
13	Is SAE J2735 BSM Part 1 transmitted via Dedicated Short Range Communications (DSRC) every 10th of a second critical for the effectiveness of the DMA bundles? Will alternate messaging protocols, such as Probe Data Message (PDM), Basic Mobility Messages (BMM), etc., suffice? Given a set of specific messages, what combinations of bundles have the most benefit? Conversely,	BSM Part 1 data transmitted every 10th of a second via DSRC is not critical for the effectiveness of DMA applications, with the exception of CACC. DMA bundles will be more effective with alternate messaging protocols in addition to BSM Part 1.

ID	DMA Research Question	Analysis Hypotheses
	given a specific combination of bundles, what messages best support this combination?	
15	Will a nomadic device that is capable of communicating via both DSRC as well as cellular meet the needs of the DMA bundles? When is DSRC needed and when will cellular suffice?	Nomadic devices that are capable of communicating via both DSRC as well as cellular will meet most of the needs of the DMA applications; however, additional data from the infrastructure will be required for DMA applications to be effective. DMA applications, with the exception of component applications of the INFLO and MMITSS bundles, will not need data to be transmitted via DSRC as higher-latency communications media (e.g., cellular) will suffice. This is not covered in the current evaluation plan.
16	What are the impacts of communication latency on benefits?	As communication latency increases, benefits will decrease. Most significant decrease will be observed for MMITSS and INFLO than for the other bundles.
17	How effective are the DMA bundles when there are errors or loss in communication?	Effectiveness of some DMA bundles will be more impacted than others due to errors or loss in communication. MMITSS and INLFO will be most impacted by errors or loss in communication.
18	What are the benefits of widespread deployment of DSRC-based RSEs compared with ubiquitous cellular coverage?	In comparison to widespread cellular coverage, widespread deployment of DSRC-based RSEs will be excessive for DMA bundles. Concentrated deployment of DSRC-based RSEs will be more cost-beneficial in highly congested urban areas than in non-urban or low to moderate congested urban areas.
21	To what extent are connected vehicle data beyond BSM Part 1 instrumental to realizing a near-term implementation of DMA applications? What specific vehicle data are the most critical, and under what operational conditions?	BSM Part 1 sent via DSRC is critical only to CACC; however other DMA applications will also need some elements of BSM Part 1 (i.e., position, speed, and acceleration) to be effective even in the near term. This is valid for all operational conditions.
22	At what levels of market penetration of connected vehicle technology do the DMA bundles (collectively or independently) become effective?	Benefits will increase with increase in market penetration of connected vehicle technology; some bundles will yield significant benefits even at lower market penetration levels.
23	What are the impacts of future deployments of the DMA bundles in the near, mid, and long term (varying market penetration, RSE deployment density, and other connected vehicle assumptions)?	Bundles that influence traveler decision-making and leverage widely deployed mobile device technology, such as EnableATIS, FRATIS, and IDTO, will yield measureable but geographically diffused system-level impacts under near-term deployment assumptions. Bundles that influence tactical driver decision-making and depend on emerging localized low-latency messaging concepts, e.g., MMITSS, Q-WARN and SPD-HARM, will yield measureable localized benefits in urban areas under near-term

ID	DMA Research Question	Analysis Hypotheses
		deployment assumptions, but limited system-level impacts until market penetration of connected vehicle technology reaches bundle-specific thresholds. This is not covered in the current evaluation plan.

Connected Vehicles and Legacy Systems

Certain DMA applications, such as INFLO, are designed to use data from connected vehicles and legacy systems, which include infrastructure-based data collection devices such as loop detectors and video/radar detection systems. For the purpose of this evaluation, the team defines connected vehicle (CV) data as high-fidelity data from vehicles including position, speed, heading, etc. Legacy system data is defined as data from any infrastructure-based system to detect vehicles and disseminate instructions back to them. This analysis used simulations with different data inputs to the applications to assess whether DMA applications will yield benefits when legacy system data is supplemented or replaced with connected vehicle data. The results were application-specific. For INFLO and MMITSS, legacy system data contributes to most benefits at lower market penetration and CV data at higher market penetration.

Under lower market penetration, legacy system data are required for DMA applications, such as INFLO and MMITSS, to achieve benefits. As market penetration increases, these applications could rely entirely on connected vehicle data. The INC-ZONE application relied completely on CV data. EnableATIS relied mostly on legacy data.

The INC-ZONE application requires CV data to work and hence were not evaluated for effectiveness under different data sources. The EnableATIS application relied mostly on legacy data and the addition of CV data caused marginal improvement in benefits. The FRATIS application was modeled in this project as a special version of EnableATIS that is applicable only to freight vehicles. In this sense, the application utilizes the link travel times from the network that, in real-life, are computed either using legacy system data or CV data. Since a distinction was not made in the data source being used inputted into the application, it was not evaluated for sensitivity towards the source of data.

The results indicate that at lower CV market penetration, DMA applications such as INFLO and MMITSS rely mostly on data from legacy systems to provide mobility benefits. However, as market penetration increases, this reliance can be replaced. For example, at 10 percent market penetration, the INFLO application provided only marginal reduction in shockwaves (less than 2 percent) when it subscribed to CV data only; whereas at 50 percent market penetration, this increased to 23 percent. However, when supplemented with data from legacy systems (represented by loop-detectors at 0.1-mile interval), INFLO reduced shockwaves by 21 percent even at 10 percent market penetration.

Compared to legacy systems, DMA applications that make use of new forms of wirelessly-connected vehicle, infrastructure, and mobile device data will yield cost-effective gains in system efficiency and individual mobility when a higher percent of vehicles can wirelessly communicate with the DMA applications. A similar trend was shown by the MMITSS application. It was demonstrated that higher reductions in arterial travel time occurred when the application supplemented CV data with detector data, compared with only providing the CV data alone. Additionally, it was shown that the MMITSS application could work without legacy system data (detector calls) when the market penetration is higher. EnableATIS applications also demonstrated greater benefits in terms of travel time reduction when legacy data was supplemented with CV data. However, this improvement was marginal and legacy data contributed to most benefits.

Synergies and Conflicts

In order to assess the impact of application combinations, MMITSS, INC-ZONE, and INFLO were assessed in isolation and in combination. It was found that these applications are synergistic in nature, with application combinations showing better performance measures than isolation at a higher market penetration of connected vehicle technology (greater than 50 percent).

At higher than 10 percent market penetration, the DMA applications which are tactical, such as INFLO, MMITSS, and INC-ZONE produced greater benefits in combination than in isolation. Strategic applications such as EnableATIS, FRATIS, and IDTO are neither synergistic nor conflicting, based on our qualitative assessment. Application combinations between the two sets also do not directly influence network characteristics in a synergistic or conflicting manner.

INFLO and INC-ZONE applications are both freeway-based applications. They were assessed in isolation and combination for reduction in shockwaves (INFLO-specific performance measure) and increase in effective throughput (INC-ZONE-specific performance measure). At market penetrations greater than 10 percent, these applications performed better in combination. For example, at 50 percent market penetration, the average reduction in shockwaves increased from 13 percent to 15 percent when INFLO was combined with INC-ZONE. The average increase in the throughput of open lanes in an incident zone increased from 50 percent to 58 percent when INC-ZONE was combined with INFLO.

INFLO and MMITSS applications were assessed in isolation and in combination for improvement in overall network delay. At any market penetration, the combination was shown to be better than isolated applications. For example, at 50 percent market penetration, the reduction in overall delay in the network increased from -1 percent (INFLO only) and 3 percent (MMITSS only) to almost 11 percent when the applications were combined. Therefore, the applications are synergistic. A similar trend was also shown for the INC-ZONE and MMITSS application combination where the reduction in average network delay increased from 2 percent to almost 5 percent. Please note that these assessments were done on specific operational conditions. An operational condition is a combination of travel demand, incident severity, and weather impacts.

The team also evaluated combinations of the tactical group of applications with the strategic group of applications using qualitative research, which looks into the specific network entity that is controlled by each application. No primary conflict or synergy was found since these groups of applications impact different aspects of the network. For example, applications such as EnableATIS, FRATIS, and IDTO impact the mode/route choice of the travelers. Applications such as INFLO, INC-ZONE, and MMITSS impact the driver behavioral parameters (e.g., speed and lane selection).

Operational Conditions, Modes, and Facility Types

The benefits from DMA applications are dependent on the operational conditions in terms of system demand, weather conditions, and incident severity. The team assessed the applications INFLO, INC-ZONE, and MMITSS in isolation and in combination under different operational conditions. EnableATIS, FRATIS, and IDTO were assessed using the Phoenix testbed. A summary of the results in terms of different operational conditions that yield maximum benefits to specific application/combination is provided in the following table. Tables ES-2 and ES-3 show the mapping of applications and their preferred facility types. The facility types are identified based on the application's functionality and design.

Table ES-2: Applications/Combinations and their Preferred Operational Conditions

Application/ Combination	*Operational Conditions that Yield Maximum Benefits*
INC-ZONE	Medium demand and high incident severity yield maximum throughput for open lanes. High demand and low incident severity yield safer (maximum reduction in) speeds for vehicles in incident zones.
INFLO	Medium demand and no incident operational conditions yield maximum benefits in terms of reduction in shockwaves and speed variations.
MMITSS	Medium demand and no incident operational conditions yield maximum benefits in terms of reduction in side-street queues. Medium demand with high incident severity yield maximum benefits in terms of arterial travel time.
EnableATIS	High demand, medium incident severity, and wet weather operational conditions provided maximum benefits in terms of travel time saved.
FRATIS	High demand and high incident severity provided maximum benefits in terms of truck travel time.
IDTO	Low demand and low incident severity provided maximum benefits in terms of travel time saved for transit passengers.
INFLO+INC-ZONE	High demand and low incident severity provided maximum benefits in terms of two of the safety-based performance measures, namely reduction in shockwaves and reduction in speeds at the incident locations.
INC-ZONE+MMITSS	Medium demand and high incident severity provided maximum benefits in terms of average network speed and delay.
INFLO+MMITSS	Medium demand and high incident severity provided maximum benefits in terms of average network speed and delay.

Table ES-3: Applications Evaluated for Different Facility Types

Application	*Favorable Facility Type*	*Reasoning*
INC-ZONE	Freeway	INC-ZONE aims to deliver alerts about incidents ahead using CV technology. Threat determination is one of the most important aspects. The application uses the vehicle

Application	Favorable Facility Type	Reasoning
		location to identify whether the incident location is along the vehicle's path, in terms of lane and heading. This is easier in a freeway setting due to the wider geographic range of the road.
INFLO	Freeway	INFLO harmonizes vehicle speeds on a roadway and, hence, is better deployed on freeways. Arterial traffic could get intermittent stops depending on the intersection control in place.
MMITSS	Arterial	MMITSS aims at optimizing signal control, which is not present in a freeway setting.
EnableATIS	Freeway/Arterial	EnableATIS uses information on travel-time, travel-speeds, incidents, etc., to provide pre-trip and en-route advisories to equipped vehicles and is therefore favored in both arterials and freeways.
FRATIS	Freeway/Arterial	FRATIS is an enhanced form of traveler information system and is therefore used in both arterials and freeways.

Messaging Protocols

The team mapped the characteristics of different messaging protocols, such as BSM, BMM, and PDM, to support different applications and assist in a qualitative assessment of which messaging protocols are optimal to each application. The mapping was based on the input requirement for each of the modeled applications. Specifically, the team identified data elements that are required to run a minimalistic DMA application (as modeled in this project) and the frequency at which this data is required to conduct this qualitative assessment. No detailed communication modeling was performed to compare the different messaging protocols. Please note that the actual input requirement might vary and a full list of inputs are provided in Appendix B along with the supporting messaging protocol.

INFLO and INC-ZONE applications, as modeled in this project, can work with input update rates that are less than 10Hz. MMITSS, as modeled, requires BSM messages at 10Hz frequency. Pre-trip and en-route messaging is critical for strategic applications such as EnableATIS.

Applications such as INFLO (SPD-HARM and Q-WARN) and INC-ZONE require messaging at a much longer frequency than 10Hz since they act on a wider area. For example, SPD-HARM acts along a freeway corridor and CV data is only used to identify harmonized speeds over sections of freeway at a minimum resolution of 5 miles per hour with an update frequency of 20 seconds. Therefore, messages such as BMM or PDM can be used in lieu of BSM messages. The MMITSS application, however, is much more localized. From the application design, it is evident that the BSM messages are instantly used to place advanced calls to the detector phases and it is imperative that these messages are delivered at the lowest latency and fastest frequency. Therefore, BSM messages are critical for this application. Our hypothesis that only some applications would require messaging at 10Hz frequency is true.

Criticality of en-route or pre-trip messaging was assessed using EnableATIS through simulations that represented different market penetration rates of variable message sign (VMS) equipage, and en-route and pre-trip route optimization. The results indicate that the en-route messaging is important in leveraging all of the application benefits. With solely pre-trip messaging, travelers may not have access to the optimum routes based on changing traffic conditions. Pre-trip and en-route messaging also indicated higher travel distance, but the travel time was always lower than the baseline.

Communication Technology

A qualitative analysis was conducted based on the different communication technologies envisioned for the connected vehicle program based on their characteristics from the literature and features required by the different DMA applications (as used in this project). Please note that a detailed communication modeling to distinguish the impact of DSRC and cellular communication was not performed in this project, but the communications impact such as latency and losses were derived from existing literature to support the qualitative analysis.

For localized and safety-critical applications, low-latency communication with neighboring devices is critical; this favors direct V2V communication through a simple medium access control protocol. DSRC (approximately 200 microsecond) would certainly fare better compared to LTE (below 5 millisecond). However, the DMA bundle applications are focused on mobility and could afford higher latency mediums. Moreover, with comparatively better latency of 4G and promise of 5G, latency issue of cellular could be easily addressed. Given that the rate of communication update required for most DMA applications is more than 0.1 second, both DSRC and cellular could satisfy the requirement and latency risk could be minimized.

DSRC is favorable for applications at a localized area that require low-latency, such as MMITSS and INC-ZONE. Applications such as SPD-HARM, Q-WARN, and EnableATIS would work with cellular communication, due to its wider coverage and larger update frequency. Nomadic devices capable of both cellular and DSRC will be a good choice for DMA applications due to this mix.

From the above analysis, a nomadic device capable of communicating via DSRC and cellular will be very useful for DMA applications. As summarized in Table ES-4, certain applications/bundles that require localized deployment work best with DSRC, whereas others work better with cellular.

Table ES-4: Summary of Preferred Medium for DMA Applications

Applications (Bundle)	Preferred Medium
SPD-HARM (INFLO)	Cellular is better due to wide coverage requirement.
Q-WARN (INFLO)	Cellular is better due to wide coverage requirement.
CACC (INFLO)	DSRC is required due to V2V safety aspect.

Applications (Bundle)	Preferred Medium
MMITSS Bundle	DSRC is better because deployment is generally localized.
INC-ZONE (R.E.S.C.U.M.E.)	DSRC is better because deployment is generally localized.
RESP-STG (R.E.S.C.U.M.E.)	DSRC is better because deployment is generally localized.
EnableATIS Bundle	Cellular is better due to wide coverage requirement.
FRATIS Bundle	Cellular is better due to wide coverage requirement.
IDTO Bundle	Cellular is better due to wide coverage requirement.

Communication Latency

Communication latency and losses significantly affect the performance of applications. This chapter assessed the impact of these communication attributes on INFLO's speed harmonization and queue warning, R.E.S.C.U.M.E.'s incident zone alerts application and the MMITSS bundle. INFLO was assessed for reduction in shockwaves and speed variations and showed that latency values beyond 3 seconds deteriorated the application performance by more than 50 percent, whereas losses beyond 10 percent virtually had zero benefits on shockwave reduction. INC-ZONE application's assessment showed that it is more sensitive to latency with almost 60 percent benefits being lost with 1 second latency. MMITSS had the highest impact due to communication latency, since it had a higher update frequency when compared to INFLO and INC-ZONE. Even a 0.5 second latency deteriorated MMITSS's benefits by over 90 percent and higher latencies caused disbenefits to the system. The impact of communication losses in INC-ZONE and INFLO were similar to reduction in market penetration.

DMA application's performance deteriorates significantly with increase in communication latency and loss-rates. Latency had the highest impact on MMITSS, followed by INC-ZONE and INFLO applications. Strategic applications were not assessed for sensitivity to communication attributes.

RSE/DSRC Footprint

Please note that the applications were assessed using modeling during this project and may not reflect the field-implemented applications. As far as the suitability of RSE coverage versus cellular coverage is concerned, a qualitative research of the application's functionality suggested that widespread RSE coverage is definitely beneficial for DMA applications. However, due to the cost and the feasibility of using cellular communication for several applications, it might be cost-effective to use a hybrid approach. For example, applications such as EnableATIS require wider network coverage and would require continuous RSE footprint if DSRC medium is used. However, applications such as MMITSS that require low-latency, high-resolution localized data at intersections require DSRC-based communication and hence RSE footprint around these localized areas (such as intersection approaches).

Widespread RSE coverage is not cost effective when applications are wide range, such as EnableATIS. However, for applications such as MMITSS, where the geographic extent is limited, RSE coverage benefits per RSE deployed might be higher.

According to existing research, while DSRC provides many benefits, for most V2I applications the cellular approach is feasible and may represent a faster adoption, lower cost, and significantly lower risk option than DSRC. The research that led to this conclusion applies to the segment of the population that can afford a smartphone with sufficient data-enabled plans.

- Faster adoption is a result of the existence of hundreds of millions of smartphones already in the field, many of which could access connected vehicle services today with the simple installation of existing applications.
- Lower cost of cellular is a result of not needing to build new infrastructure and that the hardware and software already exists.
- Lower risk arises from the fact that the cellular user base already exists while DSRC infrastructure must be deployed and requires huge investments. The added cost of equipment in cars could be risky if the consumer does not see the additional benefit compared to what the applications on their cellphone could provide.

An optimum solution may be to have a DSRC network for V2V communication complemented by a cellular network (preferably LTE) as a backup solution to address the V2I needs.

Deployment Readiness

Application and bundle performance will improve as more and more vehicles are equipped. For this assessment, the team used a combination of qualitative and quantitative assessments to see whether applications are ready to be deployed in the field and the timeframe for achieving benefits. The team performed qualitative analysis by mapping the data elements required by different prototyped applications and the data elements that are not currently in the BSM message sets. In order to assist with the quantitative assessment, the team used NHTSA's approach[3] to map near-, mid-, and long-term deployments based on a variety of factors such as deployment costs, fuel costs, fleet composition, fleet age, and turnover. The team then mapped these results with the market penetration used for this project.

Individual DMA applications showed maximum increase in benefits under near-term, when the CV market penetration around 40 to 60 percent, beyond which the rate of increase in benefits slows down.

A qualitative assessment showed that most of the DMA applications, with the exception of individual DMA applications, require connected vehicle data elements beyond BSM to function. The quantitative assessment showed a maximum increase in benefits in the near-term when the CV market penetration is up to 55 percent, beyond which the rate of increase in benefits slows down.

[3] Harding et al., NHTSA, Vehicle-to-Vehicle Communications: Readiness of V2V Technology for Application, DOT HS 812 014, August 2014.

Analysis of Deployment Costs and Benefits

This project evaluated and analyzed the costs and benefits associated with each DMA application/bundle on the San Mateo and Phoenix regions using cost-estimation and benefits-estimation models developed by the DMA program evaluation team for National-Level Impact Estimation. However, benefits and costs from this model cannot be used in a trade-off analysis, since costs developed does not account for shared costs as well as costs for deployment of DMA applications as a supplement to other applications. In addition, the costs used in this model are from the CO-PILOT tool which is only meant for high-level estimation for pilot projects and not for full-fledged deployments. However, with a lack of other sources and specific assumptions, the team evaluated the deployment costs and value of benefits from individual applications by adapting a national level model to a regional scale. 2012-dollars was used as the basis for this evaluation. The evaluation was performed to demonstrate the trends in deployment costs and the required investment components, if implemented in a manner similar to the AMS Testbed models. The benefits estimation was performed only for applications that provide direct mobility benefits.

Limitations of the Analysis

While this project aimed to provide the best evaluation of DMA applications in terms of their operations, communications, and deployment, this approach has some inherent limitations. The team made efforts to answer most research questions, but there are still several cannot be answered due to the following modeling related limitations. From a calibration perspective, DMA applications are not present in today's surface transportation sector, and therefore no data exists to calibrate an application to determine how it would affect the transportation system's performance. The applications used in this project are a reflection of their systems design and how it is intended to impact a system. Therefore, certain behavioral traits that come out from human-machine interaction or perception reaction time are not captured in this study.

Additionally, the applications and other models evaluated in this study may only be a representative of its actual field implementation. For example, certain applications designed to warn drivers were developed as a driver-behavior model that relies on application feedback as actionable commands. Similar limitations exist for other tools that were used in the process, such as a communications modeling tool. Due to the complexity and computational time required to run the simulations, only a limited number of simulations were performed for each scenario and statistical significance was assessed based only on this data. A forthcoming publication titled, “White Paper on AMS Gaps, Challenges, and Future Research” will provide additional insights into the gaps, challenges, and directions for future research to address these limitations.

Chapter 1. Introduction

The USDOT initiated the ATDM and DMA programs to achieve transformative mobility, safety, and environmental benefits through enhanced, performance-driven operational practices in surface transportation systems management. In order to explore a potential transformation in the transportation system's performance, both programs require an AMS capability. Capable and reliable AMS testbeds provide valuable mechanisms to address this shared need by providing a laboratory to refine and integrate research concepts in virtual computer-based simulation environments prior to field deployments. The primary goal of the AMS testbed project featured in this report is to develop and use AMS testbeds to evaluate the DMA applications and ATDM strategies using real-world operational conditions.

The foundational work conducted for the DMA and ATDM programs revealed a number of technical risks associated with developing an AMS testbed, which can facilitate detailed evaluation of the DMA and ATDM concepts. Therefore, instead of selecting a single testbed, a portfolio of AMS testbeds was identified to mitigate the risks posed by a single testbed approach. At the conclusion of the AMS testbed selection process, six (6) AMS testbeds were selected to form a diversified portfolio to achieve rigorous DMA bundle and ATDM strategy evaluation. They are the San Mateo (CA), Pasadena (CA), Dallas (TX), Phoenix (AZ), Chicago (IL), and San Diego (CA) testbeds. While the project aims to evaluate both DMA applications and ATDM strategies, the primary purpose of this report is to document the evaluation performed in terms of DMA applications using the AMS testbeds. The ATDM evaluation will be documented in a separate report. Primarily, San Mateo and Phoenix were used as DMA-centric testbeds to assess the DMA applications under various scenarios of application combination, communication attributes, and evaluation attributes to answer a set of research questions set forth by the USDOT.

1.1 Project Overview

The AMS project consists of using six virtual simulation based testbeds to evaluate transformative mobility, safety, and environmental benefits of DMA applications and ATDM strategies. As a result, the team identified several research questions in these two programs that could be potentially be answered by the testbeds. The project consists of several tasks and aims to document the efforts through a series of deliverables. Please note that these tasks roughly summarize the project and may not be in line with the actual project management plan due to additions of testbeds and simultaneous tasks. A list of all the publications from the AMS Project is provided in the Appendix I.

Table 1-1: AMS Project Deliverables at a Glance

No.	Milestone	Description	Deliverables
1.	Identification of Stakeholders	The team identified a number of stakeholders for different aspects to this project including DMA applications, ATDM strategies, state and local DOT personnel, Road-weather experts etc.	Stakeholder List

No.	Milestone	Description	Deliverables
2.	AMS Requirements	The team identified a set of requirements for the project based on the DMA-ATDM AMS Requirements, ATDM AMS Requirements, and DMA Bundle System Requirements Documents.	Detailed AMS Requirements Document
3.	Testbed Selection	The team selected six priority testbeds which will, in combination, cover the different aspects of the AMS evaluation objective.	Testbed Selection Report
4.	Development of Analysis Plans	The team developed test-bed specific analysis plan which details each testbed's geographic, traffic and data characteristics, the cluster analysis and calibration procedure to down-select operational conditions, scenarios, applications and strategies to be tested as well as mapping of which research questions will be addressed by the testbed.	Testbed-specific Analysis Plans
5.	Development of Evaluation Plan	Evaluation plan summarizes the individual testbed's analysis plan from a DMA and ATDM standpoint. Specifically, it addresses how the overall evaluation will address the research questions and why hypotheses will be used.	AMS Project Evaluation Plan
6.	Calibration of Testbeds	Individual testbeds are calibrated for the operational conditions identified during the cluster analysis. The task also documents the cluster analysis procedure, calibration procedure and targets and a comparison on the target performance measures before and after calibration.	Testbed-specific Calibration Report
7.	Application Modeling	The team acquired DMA applications working with prototype developers and in some cases, even developed the applications based on the System Design Document. ATDM applications were developed based on the priority functional features requested by stakeholders.	Testbed-specific Briefing
8.	DMA Evaluation	DMA Evaluation includes specific simulation-based quantitative research as well as qualitative research to answer the several research questions related to DMA applications and bundles across the different testbeds.	DMA Evaluation Report
9.	ATDM Evaluation	ATDM Evaluation includes specific simulation-based quantitative research as well as qualitative research to answer the several research	ATDM Evaluation Report

No.	Milestone	Description	Deliverables
		questions related to ATDM strategies and bundles across the different testbeds.	
10.	AMS Gaps, Challenges and Future Research	The team will develop a white paper documenting the gaps and challenges faced during the course of the project as well as some focus for future research.	White Paper

This report is a part of the DMA evaluation task and summarizes the qualitative and quantitative evaluation done for the different DMA applications and bundles.

1.2 Report Overview

This report is organized into the following chapters:

1. Chapter 1 is an introduction. It briefly describes the AMS project and provides a report overview.
2. Chapter 2, named DMA Applications Summary, describes the different DMA applications evaluated in the AMS project along with details on how they are modeled within the AMS eco-system so that combinations and special cases can be evaluated.
3. Chapter 3, named DMA Evaluation Summary, specifically describes the testbeds and research questions that they answer, along with the different operational conditions and characteristics of these testbeds. In addition, this chapter describes the key performance measures assessed in this report.
4. Chapters 4 through 12 describe the specific categories of research questions along with their assessment methodologies and research findings. These questions are mapped towards the research hypothesis so that findings can be reported. The research questions are described as defined by the USDOT.
5. Chapter 13 provides an overall summary of the report along with results, answers to the research questions, and lesson learned in the analysis.
6. Chapter 14 summarizes the limitations of the analysis with respect to the testbed and the applications evaluated.
7. Chapter 15 expands on the appendices used in this report. This includes an elaborate description of how DMA applications are modeled in this project.

1.3 Report Exclusions

While this report aims at summarizing the DMA evaluation done using multiple AMS testbeds, it currently excludes the analysis that will be done as part of the Chicago and San Diego testbeds. These testbeds were late additions to the project. Chicago will be evaluating the SPD-HARM application and San Diego will be evaluating SPD-HARM/Q-WARN, CACC, and MMITSS. Details and descriptions of these applications are provided in Chapter 2.

Chapter 2. DMA Applications Summary

This chapter summarizes the DMA bundles and applications that are evaluated in the AMS project. Specifically, six bundles of applications are included in this evaluation, and some of the applications are prototyped together. The bundles are listed below:

1. INFLO – Intelligent Network Flow Optimization
    a. Q-WARN – Queue Warning
    b. SPD-HARM – Dynamic Speed Harmonization
2. MMITSS – Multi-modal Intelligent Traffic Signal Systems (I-SIG or Intelligent Signal Control application is assessed in this evaluation)
3. R.E.S.C.U.M.E. – Response, Emergency Staging and Communications, Uniform Management, and Evacuation.
    a. INC-ZONE - Incident Scene Work Zone Alerts for Drivers and Workers
    b. RESP-STG - Incident Scene Pre-Arrival Staging Guidance for Emergency Responders
4. EnableATIS – Enable Advanced Traveler Information Systems
5. IDTO – Integrated Dynamic Transit Operation
    a. T-DISP – Dynamic Transit Operations
    b. D-RIDE – Dynamic Ridesharing
6. FRATIS – Freight Advanced Traveler Information Systems
    a. F-ATIS – Freight Real-Time Traveler Information with Performance Monitoring
    b. F-DRG – Freight Dynamic Route Guidance

The applications are classified into tactical and strategic applications.[4] Tactical applications focus on influencing decisions and maneuvers made by system users (e.g., drivers) to pre-position or control their vehicles while en-route, as well as applications that influence control/advisory decisions generated by system managers to influence these short-term tactical behaviors/maneuvers. Bundles such as INFLO, MMITSS, and R.E.S.C.U.M.E are examples of tactical applications. Strategic applications primarily influence long-term decisions made by travelers in response to traffic conditions and travel experiences. They also include applications that emulate control/advisory decisions made by system managers to influence these long-term travel choices. Applications such as EnableATIS, IDTO, and FRATIS are examples of strategic applications. Brief application descriptions and how they are modeled is provided in the following subsections. Further descriptions of the applications and their modeling approach is provided in the appendices.

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[4] Wunderlich, Vasudevan and Sandelius, Analysis, Modeling, and Simulation (AMS) Testbed Requirements for Dynamic Mobility Applications (DMA) and Active Transportation and Demand Management (ATDM) Programs, Report No. FHWA-JPO-13-098 to USDOT ITS Joint Program Office.

2.1 INFLO

The INFLO[5] bundle consists of three different applications:

1. **Q-WARN** provides a vehicle operator with sufficient warning of an impending queue backup, thereby minimizing the occurrence and impact of traffic queues by using CV technologies, including vehicle-to-infrastructure (V2I) and vehicle-to-vehicle (V2V) communications.
2. **SPD-HARM** dynamically adjusts and coordinates vehicle speeds in order to maximize traffic throughput and reduce crashes. By reducing speed variability among vehicles, traffic throughput is improved, flow breakdown formation is delayed or even eliminated, and the number and severity of collisions are reduced.
3. **CACC** or Cooperative Adaptive Cruise Control dynamically and automatically coordinates cruise control speeds among platooning vehicles, coordinates in-platoon vehicle movements, and reduces drag.

The three applications within the INFLO bundle[6] are cross-functional as described in Figure 2-1.

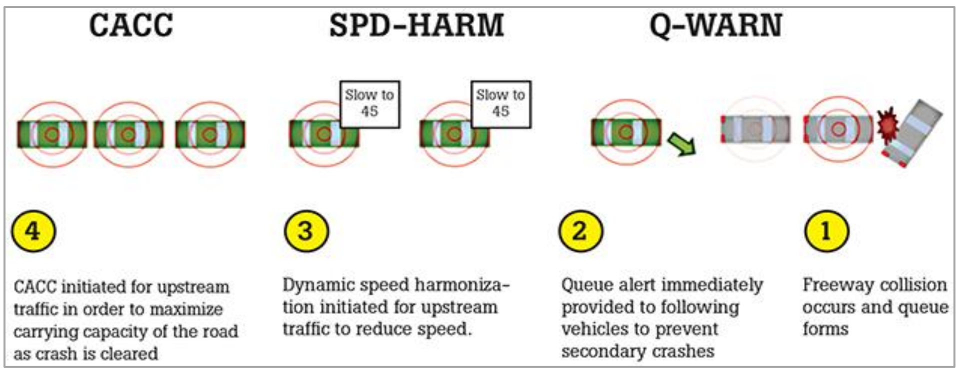


Figure 2-1: INFLO Applications Working Together [Source: TTI]

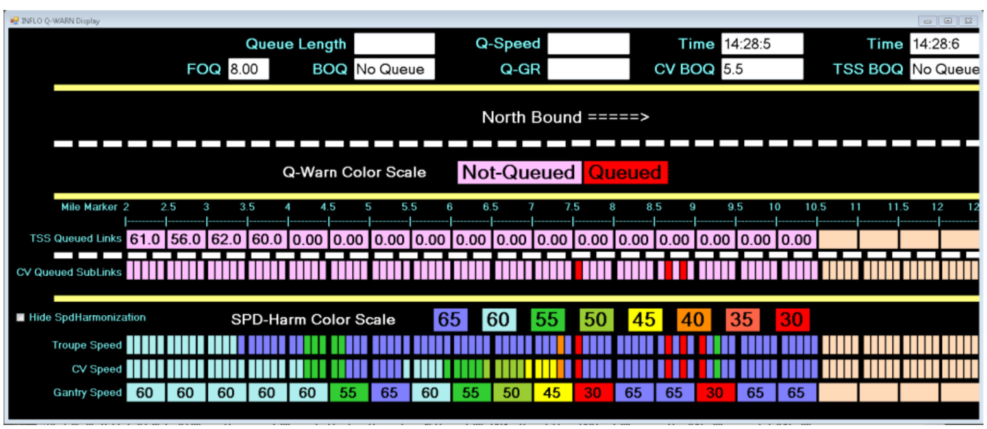


Figure 2-2: Screenshot of Q-WARN and SPD-HARM Application Developed by TTI [Source: Booz Allen]

[5] Science Applications International Corporation (SAIC), Concept Development and Needs Identification for Intelligent Network Flow Optimization (INFLO), FHWA-JPO-13-012, Accessed at: http://ntl.bts.gov/lib/42000/42300/42325/FHWA-JPO-13-012_Final_Pkg_v2.pdf

[6] Battelle, Intelligent Network Flow Optimization (INFLO) Prototype: Seattle Small-scale Demonstration, FHWA-JPO-15-223, Accessed at: http://ntl.bts.gov/lib/56000/56200/56240/FHWA-JPO-15-223.pdf

Q-WARN and SPD-HARM (referred as INFLO hereafter) were developed as a bundled Windows application (Figure 2-2) by the Texas Transportation Institute for the DMA Impacts Assessment project and was included in the evaluation in the San Mateo testbed[7]. Specifically, the applications were modeled together and used two inputs from the Vissim simulation – sensor data and connected vehicle data. Sensor data represents the loop-detector data of speed, occupancy, and volumes; in Vissim, this data came from a series of data collection measurements. Connected vehicle data represents the speed, link ID (position and heading), and queued status and was derived from Vissim using Component Object Model (COM) queries.[8] A simulation manager was created to manage the data-flow between the application and Vissim, and to control other evaluation parameters (e.g., communication). The application's data flow is described in Figure 2-3.

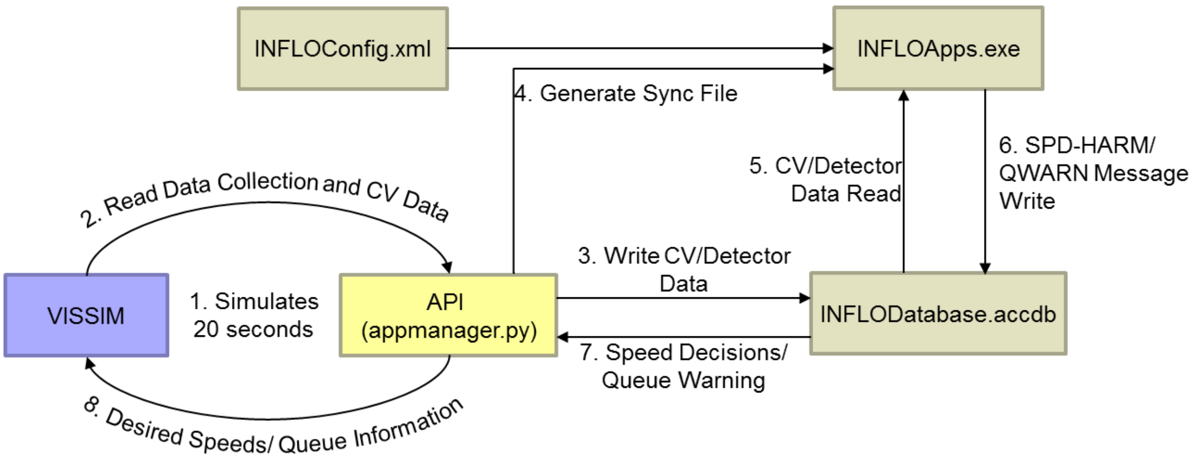


Figure 2-3: Vissim Integration of INFLO in AMS Testbeds [Source: Booz Allen]

As shown in the figure above, there are eight steps involved when INFLO application is modeled with Vissim. They are:

1. The simulation manager API (appmanager) initiates the simulation and stops it every 20 seconds, assuming the INFLO application frequency to be 20-seconds.
2. The appmanager uses Vissim's Component Object Model (COM) functionalities to query the data collection points for speed, volume and occupancy and the vehicles under CV class for location, speed, and heading.
3. The appmanager writes these data (CV data and detector data) to the Access Database, which will serve as the Input/Output socket to the INFLO application.
4. Once the data is written to the database, the appmanager generates a sync-file. The sync-file location is a location watched by the INFLO application and upon detecting the file, the application will start its computation based on the configuration settings defined in INFLOConfig.xml file.
5. When INFLO application is triggered (as in Step 4), the application will read the CV and Detector records from the database and computes harmonized speeds for each of the 0.1-mile long sublink and generates queue-warning.

[7] Texas Transportation Institute, Report on Dynamic Speed Harmonization and Queue Warning Algorithm Design, FHWA-JPO-14-168, Accessed at: http://ntl.bts.gov/lib/54000/54800/54895/FHWA-JPO-14-168.pdf
[8] Kittelson and Associates, Impacts Assessment of Dynamic Speed Harmonization with Queue Warning Accessed at: http://ntl.bts.gov/lib/55000/55300/55307/Impact_Assesment_Report_Final_2015.pdf

6. The INFLO application then writes these speeds and queue information to the database.
7. The appmanager reads the speed recommendations and the queue information generated in the database and convert them to vehicle-specific commands and desired speed decisions.
8. The appmanager uses Vissim's COM interface to provide vehicle-specific commands and alter the class-specific desired speeds at specific desired speed locations.

These eight steps are looped at 20-second intervals to emulate the INFLO application and the appmanager pauses the simulation for a specific amount of time required to run steps 2 through 8 before starting the next iteration.

The CACC application was developed by Turner Fairbanks Highway Research Center and is being utilized on the San Diego testbed to evaluate impacts.

2.2 MMITSS

MMITSS is a next-generation traffic signal system that seeks to provide a comprehensive traffic information framework to service all modes of transportation. Figure 2-4 shows an example of the MMITSS application framework where different entities at a signalized intersection could interact using CV technology. MMITSS consists of five different applications which all are prototyped together as a single application by the University of Arizona as a Software-in-the-Loop system.

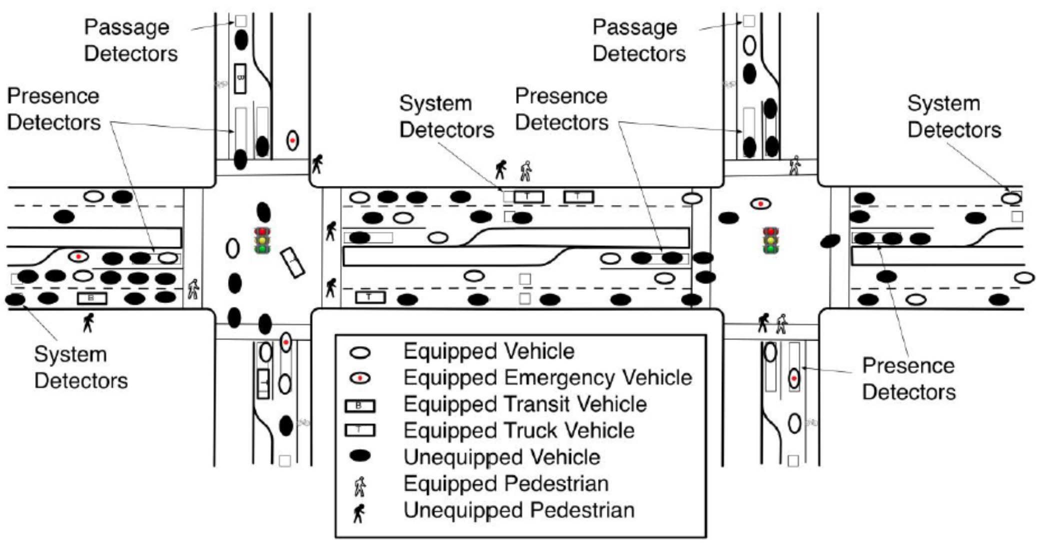


Figure 2-4: Illustration of the MMITSS Concept[9] [Source: University of Arizona]

The five applications are described below and are modeled using combinations of functions that are turned on in Linux-based Docker Containers.

1. **I-SIG** aims at maximizing the throughput of passenger vehicles and minimizing the delay of priority vehicles under saturated conditions and minimizing the total weighted delay during under-saturated conditions.

[9] Virginia Tech Transportation Institute, Multi-Modal Intelligent, Traffic Signal Systems Impact Assessment, Accessed at:
http://ntl.bts.gov/lib/55000/55700/55710/MMITSS_IA_REPORT_0811_v1.4.pdf

2. **TSP** allows transit agencies to manage bus service by adding the capability to grant buses priority.
3. **PED-SIG** integrates information from roadside or intersection sensors and new forms of data from pedestrian-carried mobile devices.
4. **PREEMPT** will integrate with V2V and V2I communication systems in preempting signal phases for emergency vehicles.
5. **FSP** provides signal priority near freight facilities based on current and projected freight movements.

The Booz Allen team has acquired the MMITSS system from the University of Arizona, who developed the application prototype. The MMITSS system is a software in the loop system and uses Vissim's Econolite/ASC3 control system to replace the innate signal control behavior using specifically designed Docker containers as explained in the Impact Assessment Report.[6] The system uses two inputs, loop-detector inputs and connected vehicle data. Loop detector inputs are collected using data collection devices at intersection approaches. Driver behavior model in Vissim is used to read vehicle data and generate BSMs to provide connected vehicle inputs to the MMITSS system. The setup is shown in Figure 2-5. For this evaluation, I-SIG is assessed using the San Mateo network since the other applications are focused at specific traveler types (e.g., freight, transit).

As shown in Figure 2-5, the MMITSS is modeled as a complex software-in-the-loop system to mimic real-world controller operations. The MMITSS application is coded to Docker Containers which are issued specific sub-net IP addresses and require two forms of inputs. The ASC/3 controllers in Vissim are coded to communicate with these containers using their IP addresses which will provide them with phasing and detector call inputs. The other input is provided by the vehicles itself in the form of Basic Safety Messages. BSMs are generated by the CV class of vehicles using BSM-generating driver-behavior models. These models communicate the BSMs to a BSM emulator which classifies them to the Road-Side-Equipment which is in its range. Based on the RSE-mapping, each of these BSMs go to their specific MMITSS containers to form the second set of inputs. Using these two inputs, the containers produce NTCIP commands to intelligently control the ASC/3 controllers which are provided as output to the specific controller files.

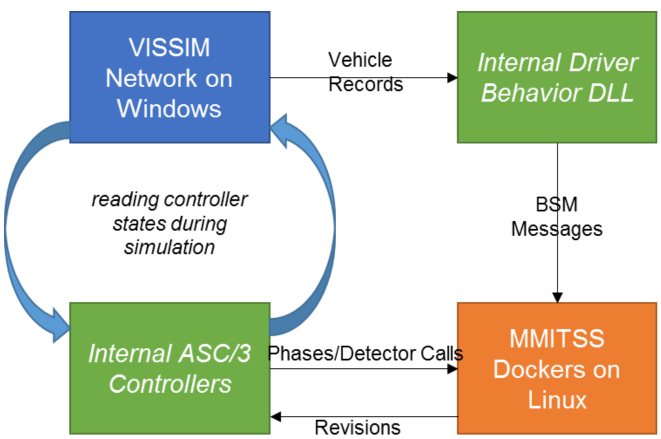


Figure 2-5: MMITSS Integration in AMS Testbeds [Source: Booz Allen]

2.3 R.E.S.C.U.M.E.

The R.E.S.C.U.M.E. bundle consists of three different applications:

1. **EVAC**[10] supports region-wide evacuations. It provides dynamic route guidance information for those using their own transportation and provides information to identify and locate people for those requiring assistance.
2. **RESP-STG** is a responder staging application that aims at enhancing situational awareness and coordination among emergency responders by providing valuable inputs to responder and dispatcher decisions and actions.
3. **INC-ZONE** is an incident zone application. It warns drivers that are approaching temporary work zones at unsafe speeds and/or trajectory. It also warns public safety personnel and other officials working in the zone.

The prototypes for RESP-STG and INC-ZONE were developed by Battelle and were later ported to a simulation-based API by Booz Allen for the Impacts Assessment project[11]. This simulation-based API was used in the San Mateo testbed for evaluation. The EVAC algorithm was not integrated into the AMS testbeds since the prototyped application is on a regional macroscopic scale and AMS testbeds are built on a microscopic scale. The applications INC-ZONE and RESP-STG uses Vissim's COM capability to continuously monitor vehicle speeds and uses the threat-determination logic described in the System Design Document to issue vehicle commands to reduce desired speed and change desired lane selection parameters of vehicles. The software setup is shown in Figure 2-6.

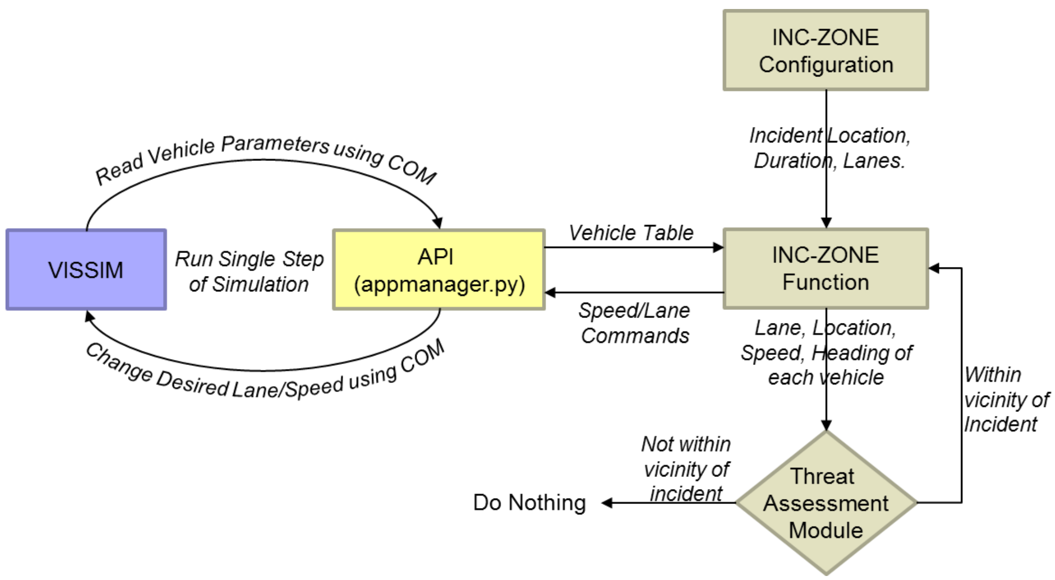


Figure 2-6: Modeling of INC-ZONE and RESP-STG Applications in Vissim [Source: Booz Allen]

As shown in the figure above, INC-ZONE is managed by the appmanager, which reads the vehicle parameters using COM and sends the vehicle table to the INC-ZONE function. This function finds the vehicles that are within the alert, warning, or advisory distances for the incident defined in the INC-ZONE configuration file. This step is called "threat determination." Vehicles without any threat are ignored and

[10] Booz Allen Hamilton, Emergency Communications for Evacuation (EVAC) in New Orleans Impact Assessment Report, Accessed at: http://ntl.bts.gov/lib/55000/55000/55045/R_E_S_C_U_M_E__EVAC_IAReport_FINAL_FHWA-JPO-15-204.pdf

[11] Booz Allen Hamilton, Impact Assessment of Incident Scene Work Zone Alerts for Drivers and Workers (INC-ZONE) and Incident Scene Pre-arrival Staging Guidance for Emergency Responders, Accessed at: http://ntl.bts.gov/lib/55000/55000/55047/R_E_S_C_U_M_E__INC-ZONE_RESP-STG_IAReport_FINAL_FHWA-JPO-15-203.pdf

the other vehicles are issued speed or lane-change commands based on their distance from the incident and their relative lane positions. The appmanager generates these commands and feeds to the Vissim simulation using desired lane and desired speed functions in COM. The application code is available in the Open Source Applications Development Portal (OSADP) at www.itseforge.net.

2.4 EnableATIS

EnableATIS[12] consist of four different applications:

1. **ATIS -** Multimodal Real Time Traveler Information that integrates travel-time reliability in a multimodal environment by integrating data from different sources and disseminates it to users via different media.
2. **S-PARK** - Smart Park and Ride that monitors and reports the occupancy of parking spaces in real time, calculates the average travel distance and time to the parking facility, and suggests alternative locations.
3. **T-MAP** - Universal Map Application that enables transportation agencies to place real-time information on a universal map by addressing the issue of proprietary map applications.
4. **WX-INFO** - Real Time Route Specific Weather Information which provides real-time, highly localized weather information with the objective of improving the mobility and safety of users of motorized and non-motorized modes of transportation

Since the application[13] was not prototyped before, an ATIS application was developed for the Phoenix testbed encompassing some of the attributes of EnableATIS. The developed version simulates vehicle/driver decision-making and travel using the following key functions:

1. Share information on real-time road conditions and network traffic to EnableATIS
2. Share information on predicted travel times for any specified vehicle/driver to EnableATIS
3. Based on specified compliance rate and assumed driver decision-making model, simulate passenger mode-choice and attendant vehicle/driver route decisions
4. Simulate resultant trips through the network and continuously provide real-time information, such as real-time road/traffic conditions and travel-times for driver decision making.

Functionalities that are reliability-based or experience-based, parking, mapping, or weather related were not included in this limited evaluation.

EnableATIS will provide a time-dependent shortest path from origin to destination for travelers (pre-trip planning) or from the current location to destination (en-route planning). Agent-based modeling is used to model the application and the simulation consists of traveling agents that could be travelers in SOV, HOV, or transit. With EnableATIS, we know the agent's historical routes, departure time, and the specific location of the agent when an incident is detected. In real applications, the agents' location can be obtained based on probe data, such as GPS traces sent to the server. To capture the complex flow balance relationships for travelers along with different types of information, we benefited from space-time network modeling and agent-based optimization. However, despite giving a global view and a system optimal solution, solving analytical models in a large scale is very challenging. At the same time, a

[12] Noblis, EnableATIS Strategy Assessment, Accessed at: http://ntl.bts.gov/lib/52000/52600/52622/FHWA-JPO-14-113-v1.pdf

[13] Kimley-Horn and Associates, Vision and Operational Concept for Enabling Advanced Traveler Information Services: Operational Concept, Accessed at http://ntl.bts.gov/lib/45000/45900/45929/Final_Package_FHWA-JPO-12-052_508.pdf

simulator is limiting because agents only follow local rules without a global view. Furthermore, agents impact the system through their own behavior and interactions with other agents. Therefore, the application was modeled by introducing a decentralized (DEC) optimization process to optimize critical values of travel time and achieve system optimum. A Lagrangian Relaxation-based heuristic approach was used and was implemented in DTALite for solving this. DTALite could spontaneously reflect the capacity constraints of this optimization problem and since most of the constraints could easily be met or handled in a simulation, the analytical optimization model was reduced and solved through a Lagrangian algorithm using the DEC algorithm. The general algorithm used in EnableATIS is presented in Figure 2-7. More details on the application logic is presented in Appendix B.

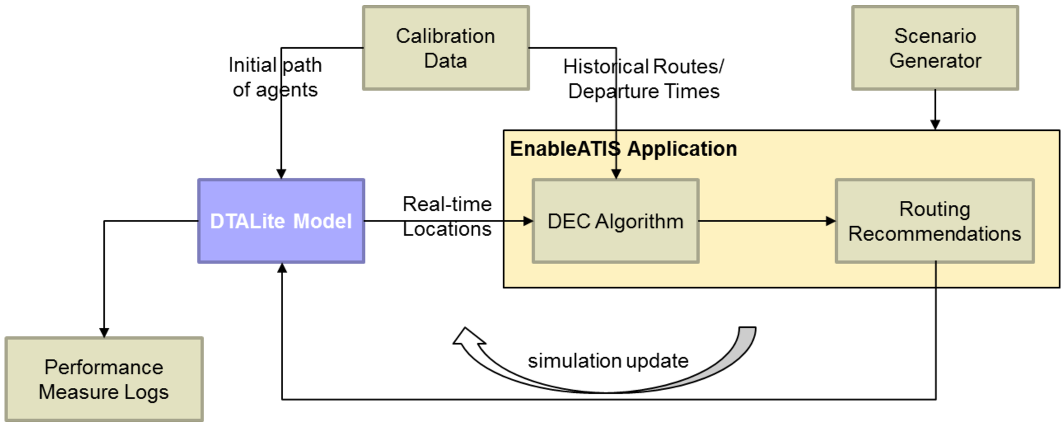


Figure 2-7: Modeling EnableATIS in Simulation [Source: Booz Allen]

2.5 IDTO

IDTO[14] consists of three different applications:

1. **T-CONNECT** aims to improve rider satisfaction and reduce expected trip time for multimodal travelers by protecting transfers between both transit and non-transit mode and facilitating coordination between multiple agencies.
2. **T-DISP** aims at advancing demand-responsive transportation services using existing technology systems and expanding transportation options. It seeks to match travelers' requests for trips with available transportation providers' services.
3. **D-RIDE** is a car-pooling system that provides drivers and riders with the flexibility of making real-time transportation decisions and aims at increasing the use of non-transit ride-sharing options including carpooling and vanpooling, and improving the accuracy of vehicle capacity detection.

The IDTO bundle[15] was prototyped as a mobile device application by Battelle. T-CONNECT and T-DISP were prototyped together as a single mobile device application "Connect and Ride."

The Booz Allen team evaluated functionalities of the T-CONNECT application and due to the extended scope of work it would require for integration, it was not evaluated in the AMS project. T-CONNECT simulation requires assigning passengers in vehicles (including transit vehicles) in the simulation model,

[14] Battelle, Prototype Development and Demonstration for Integrated Dynamic Transit Operations, Accessed at: http://ntl.bts.gov/lib/57000/57000/57028/FHWA-JPO-16-276.pdf
[15] Volpe Center, Impacts Assessment of Integrated Dynamic Transit Operations: Final Report, Accessed at: http://ntl.bts.gov/lib/59000/59000/59015/DOT-VNTSC-FHWA-16-11.pdf

and holding buses and transit vehicles to make a connection after a request to hold is acknowledged and accepted. This requires significant additional features not available in current simulation testbeds. Currently, passengers/people in the Phoenix testbed appear only in the decision-making activity of selecting a start time and a route. After that the simulated entity is a vehicle with a given number of passengers.

The Phoenix testbed team has reviewed the system design and architecture documentation for the T-DISP application and developed some of the T-DISP functionalities into the Phoenix testbed model. When the demand responsive schedule for bus/transit is available to the simulation testbed, the simulated traveler will either be picked-up at the origin at the scheduled time, or the simulated vehicle with the traveler will be directed to the bus/transit stop. The testbed will provide predicted arrival times of passengers to the T-DISP application. Some of the functionalities of D-RIDE were also modeled in the Phoenix testbed. Specifically, the D-RIDE application was modeled as a vehicle routing problem with pickup and delivery time windows where passengers may share their trip for a portion of their trip. The algorithm is defined as an optimization problem with a specific origin and destination for each traveler, departure and arrival time-windows, and a set of other rules defined to constrain vehicle capacity, passenger wait time, cost of travel, and empty trips. The system was coded to use time-dependent dynamic programming to reach a solution. D-RIDE application requires recording passengers' waiting, picking-up, and dropping-off status. It also requires recording the vehicle-to-passenger paring process in the simulation model. In reality when the vehicle-to-passenger assignment and routing schedule are available, the traveler will either be picked-up at the origin at the scheduled time, or the vehicle with passengers will be routed through externally specified data interfaces from the ride-share application. Figure 2-8 and Figure 2-9 shows the logical steps used by T-DISP and D-RIDE to work with the DTALite model.

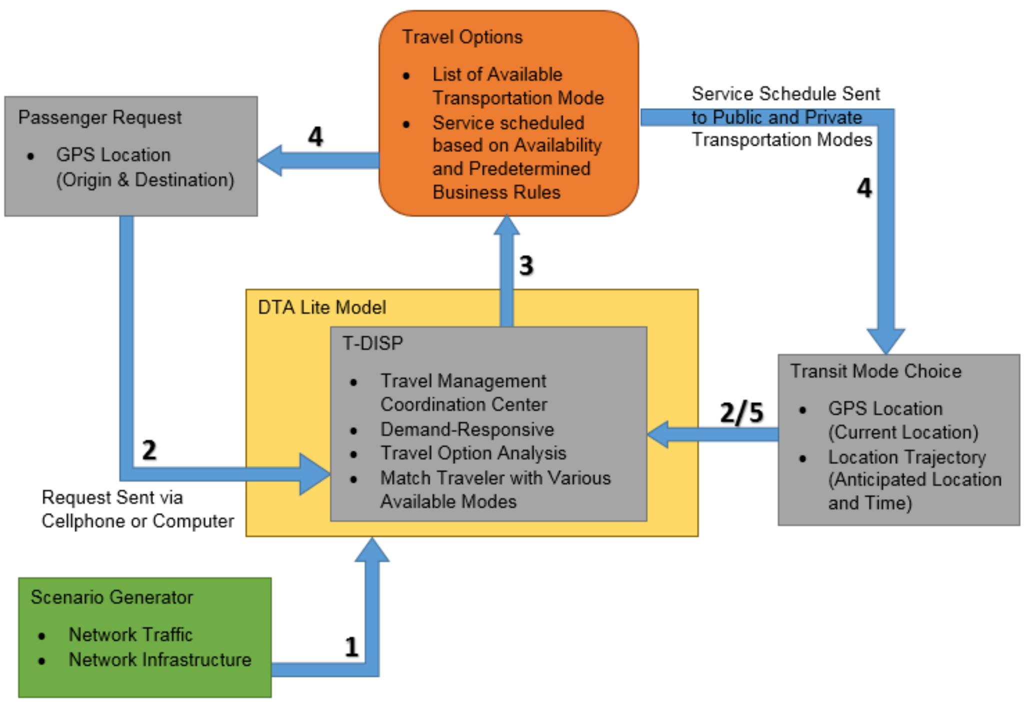


Figure 2-8: Logical Diagram of T-DISP Interacting with DTA-Lite [Source: Booz Allen]

As shown in Figure 2-8, the T-DISP application requests locations of origins and destinations of "equipped" travelers and service schedule to match them with transit and provides this to the DTALite model, which in turn determines use of the recommended path based on the traveler schedule. T-DISP is developed as a DTALite module which utilizes 4 other modules for its functioning. The scenario generator generates a log of the network demand and infrastructure characteristics. The Transit Mode Choice module tracks the transit vehicles in terms of their occupancy, location, route etc. The Passenger Request module tracks the transit O-D in terms of the pick-up and delivery locations and time-windows of the vehicles. The T-DISP Travel Options module utilizes the transit mode choice module and passenger request module to optimize the dispatch of transit vehicles based on the real-time link-travel-time information provided by the DTALite.

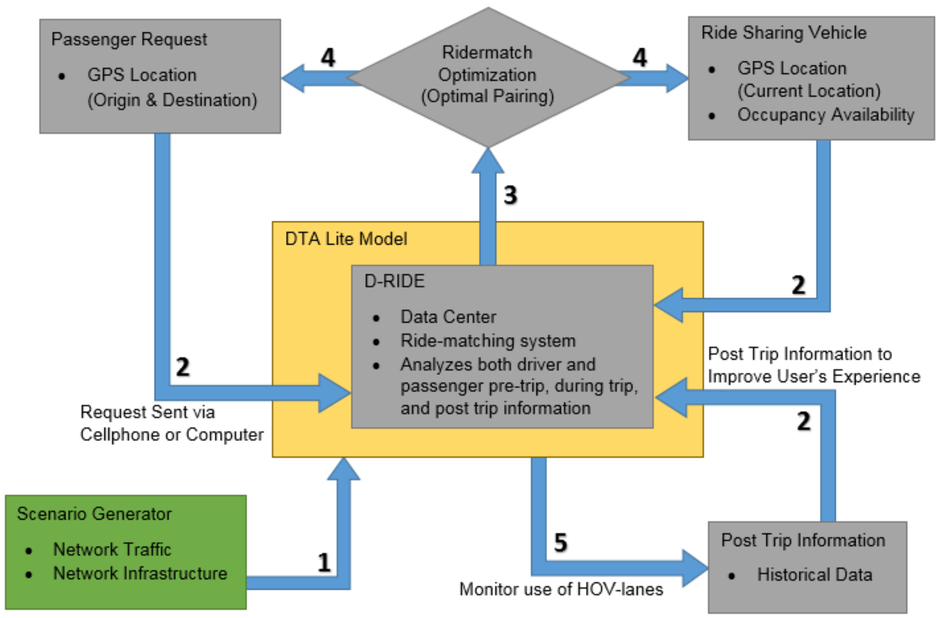


Figure 2-9: Logical Diagram of D-RIDE Interacting with DTA-Lite [Source: Booz Allen]

As shown in Figure 2-9, D-RIDE uses a Ridermatch pairing algorithm to match individual traveler's time-dependent O-D with available vehicle's schedules and occupancies. The Ridermatch Optimization module utilizes two inputs – Passenger Request tables which shows the pick-up and delivery locations with departure time windows and Ride Sharing Vehicle list with location and occupancy availability. The optimization model then ride-matches passengers to vehicles based on their origin, destination and historic link travel times. Further details on this algorithm is provided in Appendix H.

2.6 FRATIS

FRATIS[16] consists of three different applications that are freight-related:

1. **DR-OPT** combines container load matching and freight information exchange systems to fully optimize drayage operations using powerful algorithms to leverage data from multiple sources.
2. **F-ATIS** and **F-DRG** are modeled as a single application called Freight Specific Dynamic Travel Planning and Performance. It includes all of the traveler information, dynamic routing, and performance monitoring elements that freight-truck users need in one application and leverages existing data in the public domain, as well as emerging private sector applications.

FRATIS[17] is, in essence, a special ATIS system for logistics. It shares many similarities with EnableATIS. However, the major focuses of FRATIS are different from EnableATIS. For example, in addition to benefiting trucks everywhere via dynamic routing suggestions, FRATIS may be especially beneficial to trucks via proper scheduling at certain locations, such as ports, terminals, or borders. Another major difference between FRATIS and EnableATIS, more importantly, is the number of destinations. General travelers typically plan one destination per trip whereas the truck drivers most likely need to plan multiple destinations upfront to deliver or pick up goods. There are two types of FRATIS applications, long-haul freight transportation system in which routing guidance is performed across cities or even states; and multi-destination drop-offs and pick-ups (such as grocery store chains) within metropolitan areas. Figure 2-10 demonstrates the high-level diagram of the prototyped FRATIS application under DMA Programs Prototype Development Project.

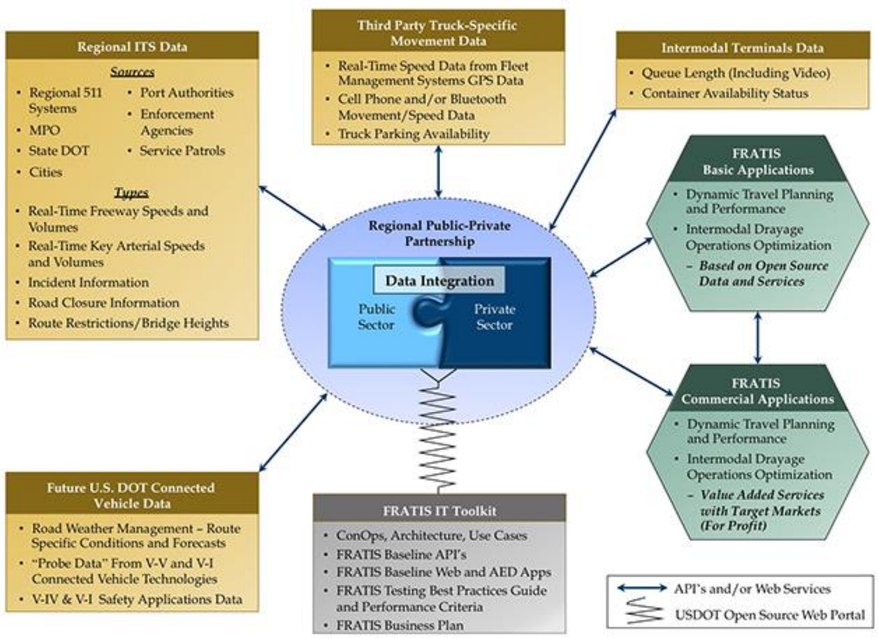


Figure 2-10: Proposed High-Level System Concept for FRATIS Application[18] [Source: Booz Allen]

[16] Leidos, Freight Advanced Traveler Information System (FRATIS) - Dallas Fort Worth (DFW) Prototype: Final Report, Accessed at: http://ntl.bts.gov/lib/55000/55300/55302/fratis_dfw_final_6_23_15.pdf
[17] CDM Group, Freight Advanced Traveler Information System (FRATIS) Impact Assessment, Accessed at: http://ntl.bts.gov/lib/57000/57000/57031/FHWA-JPO-16-225.pdf
[18] http://www.its.dot.gov/dma/dma_development.htm

Mathematically, the route guidance problem for trucks can be viewed as a special version of the vehicle routing problems. In particular, during a truck trip, the truck needs to decide a proper sequence to visit those locations. Solving vehicle routing problems (VRP) is typically very difficult when problems become large-scale and therefore a fast heuristic algorithm based on finding the minimum total cost for all possible visiting sequences is developed in FRATIS to provide guidance for trucks. The origin and destination, departure and arriving time window from origin and for each destination for each truck, the sketched road network with link travel time information and evaluation benchmark such as total travel time should be given to the algorithm as an input.

The AMS team has acquired the final version of the DFW and LA versions from the Open Source Portal. The application uses C# development environment with six different external dependencies and use of proprietary software. The FRATIS bundle is being prototyped in California, Florida, and Texas. However, the acquired algorithm is difficult to use within a simulation context due to its external dependencies. The AMS team, understanding the significance of the application, has developed a DTALite version of the FRATIS application to use within the Phoenix testbed. For the Phoenix testbed, freight will be treated as a vehicle fleet with specific freight loading and routing attributes. Each vehicle (trucks) in the fleet will have its traffic flow properties. Furthermore, the origin and destinations, with timing attributes, will be provided externally. The only way this fleet will interact with the rest of the vehicles in the network is that part of the network will be used by both trucks for freight and passenger vehicles and as such they will experience the same congestion and travel times. The DTALite version of FRATIS can determine optimal visiting sequences of destinations for trucks with multiple destinations. The application also enables recalculating these sequences and routes according to updated travel-times throughout the simulation.

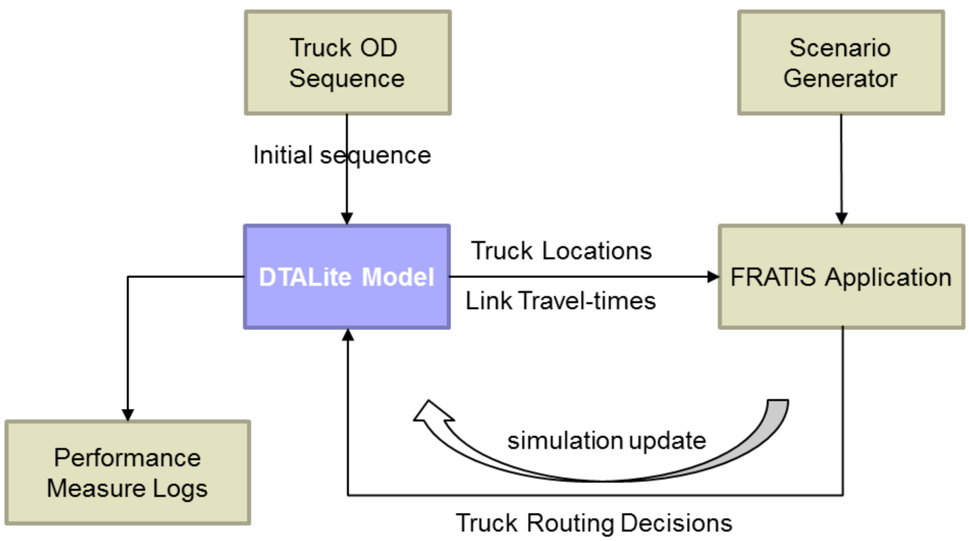


Figure 2-11: Modeling of FRATIS [Source: Booz Allen]

2.7 Summary

As described in this chapter, the project team utilized and sourced some of the existing codes and models for modeling and simulation of DMA Applications. Table 2-1 provides a summary of the applications used in this project and their source and model description. The description also provides brief differences between how the application is modeled and the original system design

Table 2-1: Summary of DMA Applications

Application	Testbed	Source	Description
EnableATIS	Phoenix	ASU modified the Dynamic Routing module within DTALite for this project	Developed as a DTA-Lite Tool, this application reroutes individual vehicles to an optimal route based on link-based travel times. Dependency on other factors such as weather is not included in this model. Additionally, the features such as departure-time and mode-choice changes are also not modeled in this application.
FRATIS	Phoenix	ASU developed a limited prototype for this project.	Developed as a DTA-Lite Tool, this application reroutes individual trucks to an optimal route based on link-based travel times. Additionally, the application also optimizes delivery and pick-up sequence when there are multiple delivery points. Features such as departure time adjustment, dependency on weather, terminal congestion etc. are not modeled in this application.
T-DISP	Phoenix	ASU developed a simulation version for this project.	Developed as a DTA-Lite Tool, this application enables dynamic dispatch of transit vehicles along a route based on traveler demand. Features such as dynamic transit routing to drop-off passengers and dynamic transit mode choice are not modeled.
D-RIDE	Phoenix	ASU developed limited prototype for this project.	Developed as an independent tool, dynamic ride-sharing matches drivers and passengers based on vehicle capacities, location, departure and arrival times. The application is not fully integrated with DTALite, but provides a pre-optimization model to match traveler demand in the network. D-RIDE optimization can be visualized using NEXTA.
INFLO (SPD-HARM and Q-WARN)	San Mateo	Developed by TTI for the Impact Assessment project.	C-Sharp based executable utilized for the Impact Assessment[19] was used in this project. The team developed a Python-based Vissim COM API to interact with the testbed and form a closed-loop simulation system.

[19] Kittelson and Associates, Impacts Assessment of Dynamic Speed Harmonization with Queue Warning Accessed at: http://ntl.bts.gov/lib/55000/55300/55307/Impact_Assesment_Report_Final_2015.pdf

Application	Testbed	Source	Description
MMITSS (I-SIG)	San Mateo	Developed by UA for the Impact Assessment project.	Linux-based Docker applications developed for Impact Assessment[20] was used in this project. Communicating via CV and NTCIP protocols was enabled between MMITSS and Vissim to enable a Software-in-the-Loop system.
R.E.S.C.U.M.E. (INC-ZONE)	San Mateo	Developed by Booz Allen for the Impact Assessment Project.	Python-based Vissim COM API utilized for the Impact Assessment[21] was used in this project.

[20] Virginia Tech Transportation Institute, Multi-Modal Intelligent, Traffic Signal Systems Impact Assessment, Accessed at: http://ntl.bts.gov/lib/55000/55700/55710/MMITSS_IA_REPORT_0811_v1.4.pdf

[21] Booz Allen Hamilton, Impact Assessment of Incident Scene Work Zone Alerts for Drivers and Workers (INC-ZONE) and Incident Scene Pre-arrival Staging Guidance for Emergency Responders, Accessed at: http://ntl.bts.gov/lib/55000/55000/55047/R_E_S_C_U_M_E__INC-ZONE_RESP-STG_IAReport_FINAL_FHWA-JPO-15-203.pdf

Chapter 3. DMA Evaluation Summary and Research Hypotheses

3.1 DMA Evaluation Summary

In this report, six DMA applications and bundles are evaluated over two virtual computer-based simulation testbeds – San Mateo and Phoenix – and the results are used to answer a set of research questions described in this chapter. Each of these testbeds was used to evaluate three different sets of DMA applications, as shown in Figure 3-1.

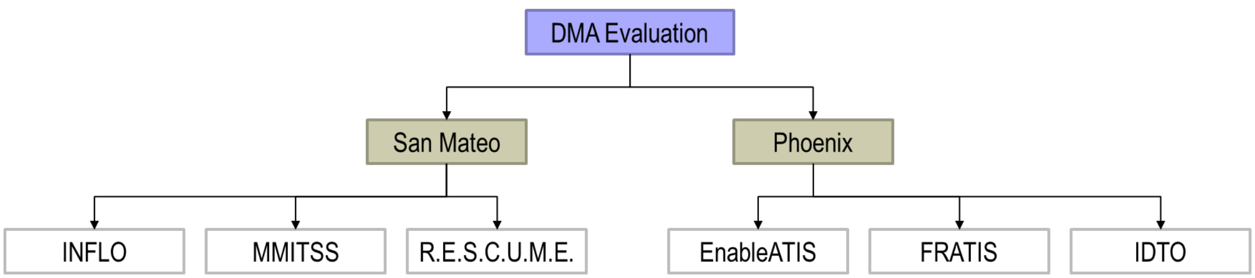


Figure 3-1: DMA Evaluation Testbeds and their Corresponding Applications [Source: Booz Allen]

3.2 DMA-Specific Testbeds

The AMS testbed project spans over six testbeds, namely San Mateo, Phoenix, Dallas, Pasadena, Chicago, and San Diego. However, San Mateo and Phoenix were the primary DMA-specific testbeds and are used in this report.

3.2.1 San Mateo

The San Mateo testbed is an 8.5-mile-long stretch of the US-101 freeway and State Route 82 (El Camino Real) in San Mateo County, located approximately 10 miles south of the San Francisco International Airport (SFO). The coast range bounds the corridor on the west side. The San Francisco Bay bounds the corridor on the east side. State Route 92 (with the San Mateo Bridge) is the only east-west connector in the corridor that extends beyond the physical boundaries of the corridor. SR-92 goes from the Pacific Coastline through the coast range and across the San Francisco Bay to Hayward on the east side of the Bay. All north-south traffic on the west side of the Bay is limited to the US-101 freeway, El Camino Real, and Interstate 280 (not included in the testbed).

This testbed accounts for non-holiday 5-hour afternoon peak period between 2:30 pm and 7:30 pm. Figure 3-2 shows the geographic overlay map of the testbed.

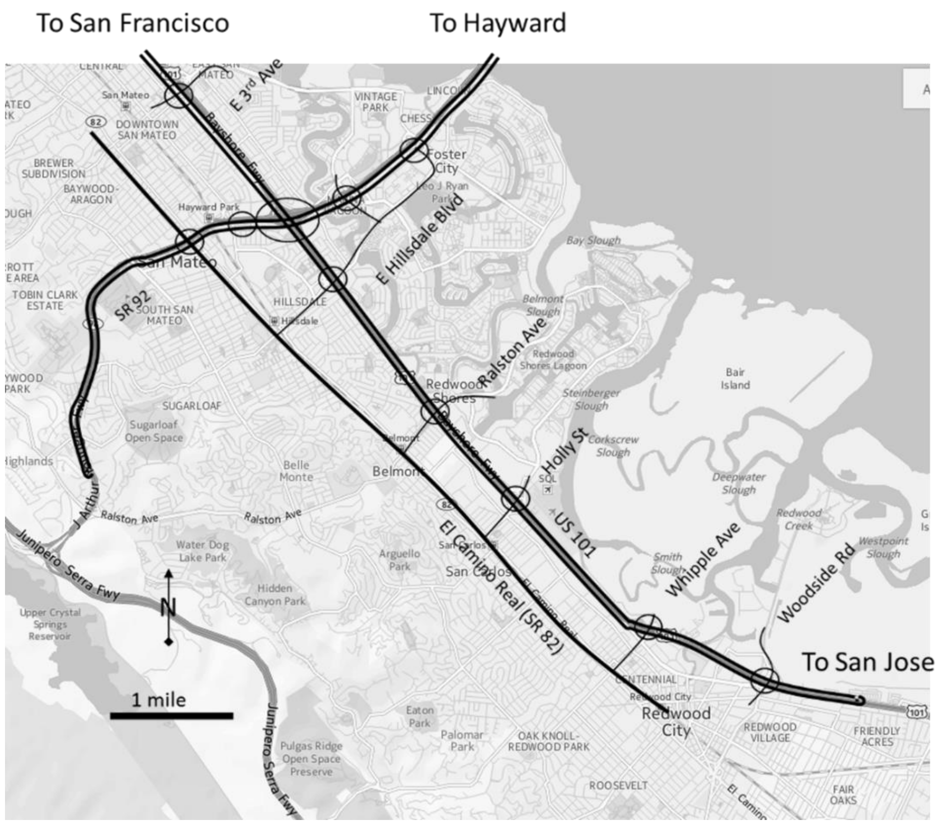


Figure 3-2: San Mateo Testbed [Source: Booz Allen]

In addition to using different transportation modes, in order to achieve the AMS project goals, the San Mateo testbed used specific modeling tools to add capabilities such as wireless communication. As shown in Figure 3-3, the testbed used an application manager to specify scenarios that can be run to answer different research questions using applications in isolation or in combination, as well as other modeling parameters such as communication latency, communication losses, etc. The DMA application manager uses COM capabilities to initiate and manage Vissim simulations for the scenarios tested but turning applications on and off as needed. The performance measures aggregator, coded in R, uses vehicle records to aggregate the performance measures for each run. Overall network performance measures are directly generated by Vissim. The communications emulator used for INFLO and R.E.S.C.U.M.E. assessment was Trajectory Conversion Algorithm[22]. For the MMITSS application, the team modified a built-in BSM Generator to incorporate latencies and losses.

The three tactical DMA bundles/applications, namely INC-ZONE, INFLO, and MMITSS, are primarily modeled in the San Mateo testbed. Since these applications work on different facility types and situational extents, they operate specifically at different geographic locations. This is shown in Figure 3-4. As shown, INFLO is coded to work with the US-101 NB freeway and accesses both vehicle and infrastructure attributes from that location to work. INC-ZONE is specific to the incident area and its geographic extent is limited to 0.5 mile upstream of incident locations. As shown, MMITSS applications are modeled to work in eight of the north-most intersections on El Camino Real arterial extending from SR-82 and 20th Avenue in the north until SR-82 and 38th Avenue in the south.

[22] TCA was developed by Noblis and is available for download at http://www.itsforge.net/index.php/tca-2-3-3

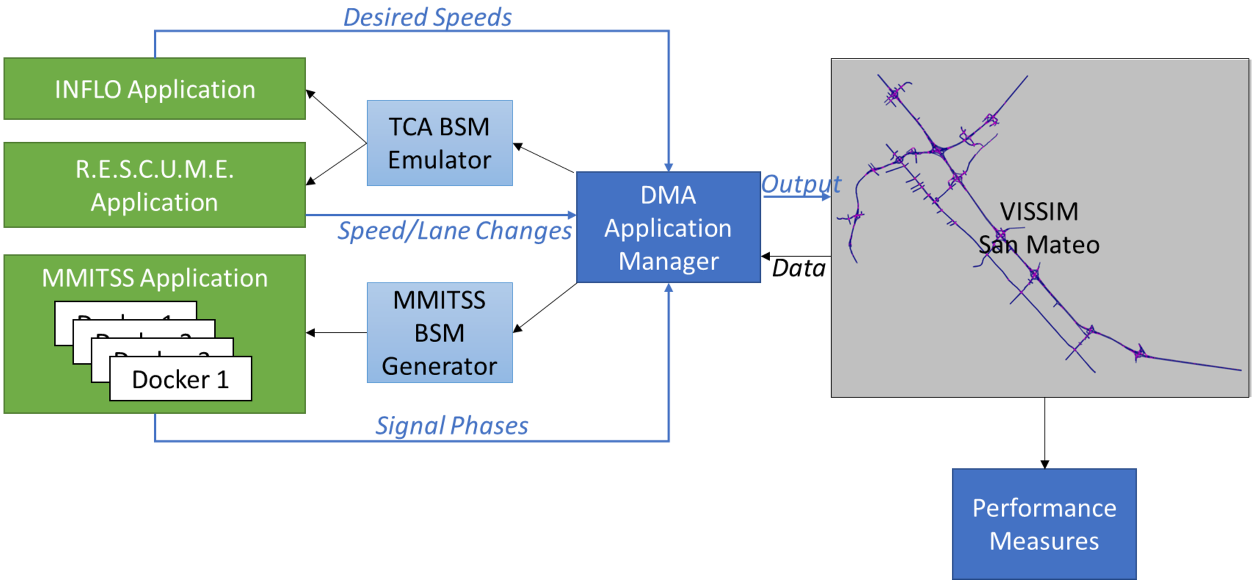


Figure 3-3: Modeling Tools Used in San Mateo Testbed [Source: Booz Allen]

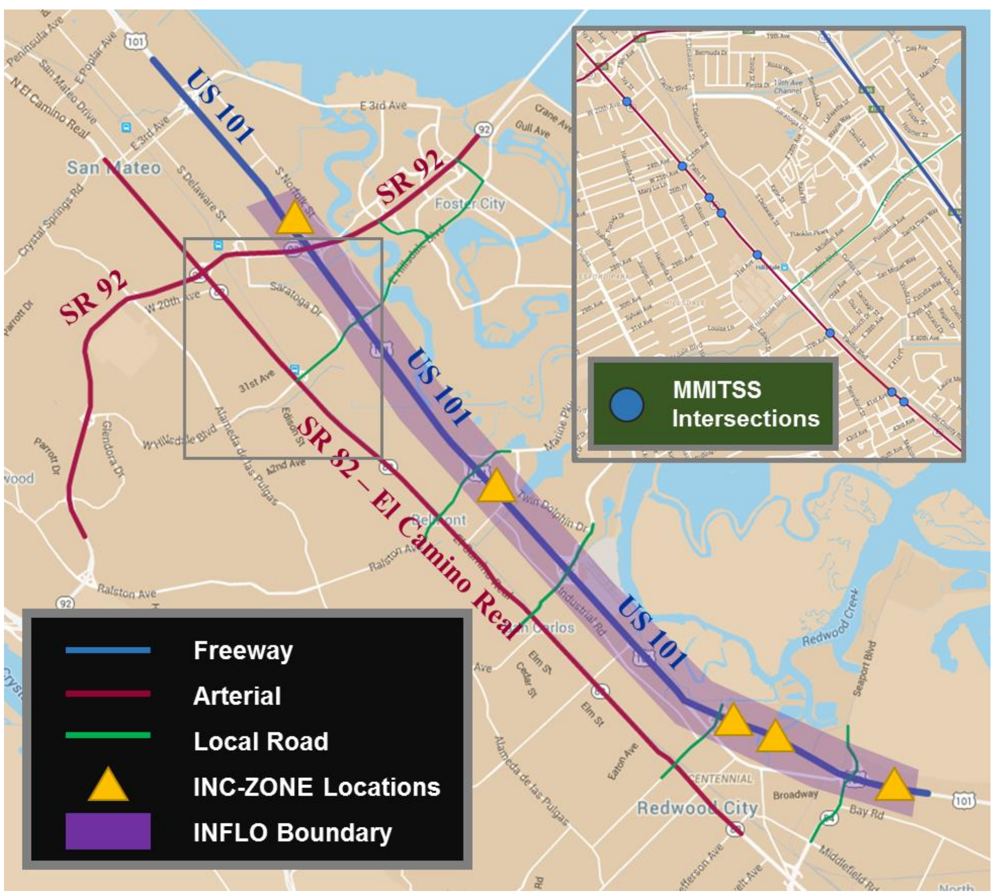


Figure 3-4: Geographic Extent of DMA Applications [Source: Booz Allen]

3.2.2 Phoenix

The Phoenix testbed covers the entire Maricopa Association of Governments (MAG), which is home to more than 1.5 million households and 4.2 million inhabitants. This multi-resolution simulation model considers multiple modes, such as single/high occupancy vehicles, transit buses and light-rail, and freight vehicles. The region covers an area of 9,200 square miles and is characterized by a low-density development pattern with population density just about 253 people per square mile. The region has one city with more than one million people (Phoenix) and eight cities/towns with more than 100,000 people each. The region has experienced dramatic population growth in the past two decades, with the pace of growth slowing rather significantly in 2008-2012 period in the wake of the economic downturn. The region is home to the nation's largest university (Arizona State University with more than 73,000 students), several special events centers and sports arenas, recreational opportunities, a 20-mile light rail line, and a large seasonal resident population. The focus of the testbed is the Tempe area, which covers an area of 40 square miles. This testbed only considers afternoon peak traffic between 3:00 pm and 7:00 pm. Figure 3-5 shows the geographic overlay map of the testbed along with the traffic analysis zones in DTALite (Dynamic Traffic Assignment Tool).

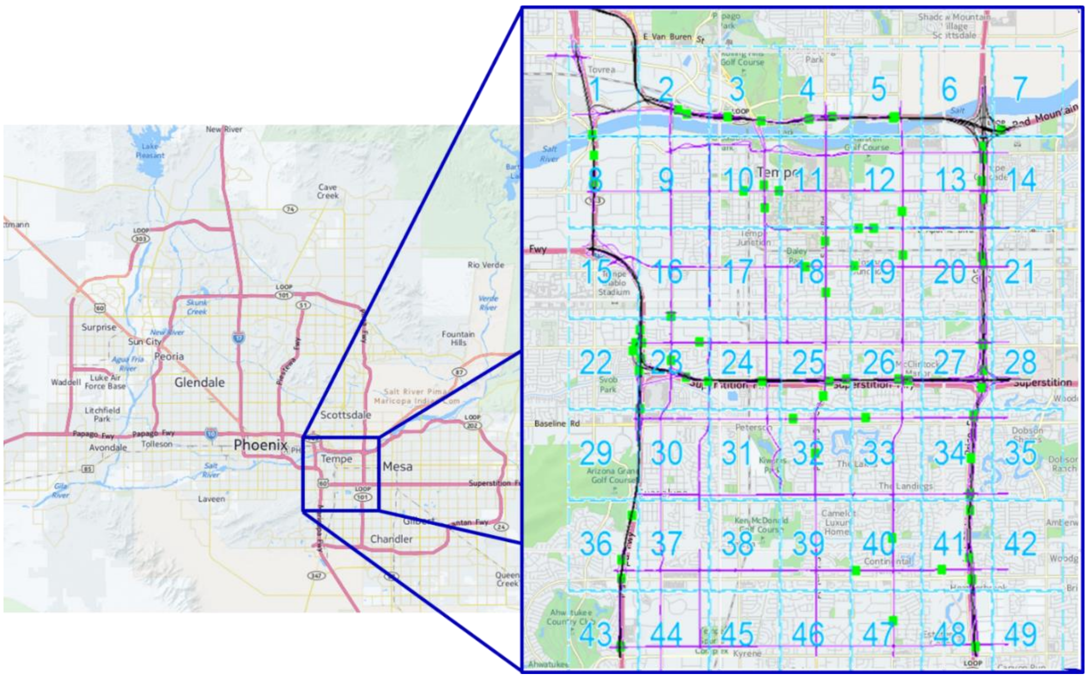


Figure 3-5: Phoenix Testbed [Source: Booz Allen]

Specifically, the Phoenix testbed will be used to evaluate the three strategic DMA applications – EnableATIS, FRATIS, and IDTO. The testbed was calibrated for four operational conditions with varying travel speeds, traffic demand, and incident severity. These are described in the baseline section 3.3.2.

Figure 3-6 shows the modeling framework used for Phoenix testbed. As shown, the testbed is a subset of the Greater Phoenix regional DTA (Dynamic Traffic Assignment) network and focuses on the City of Tempe. The network was calibrated using Origin-Destination Matrix Estimation using agent-based trajectory extraction and OD-cut processes. The calibration process is explained in the Testbed's Calibration Report [Report Number: FHWA-JPO-16-379]. The calibrated DTALite model is used with the three DMA applications to generate the specific performance measures for each scenario simulated.

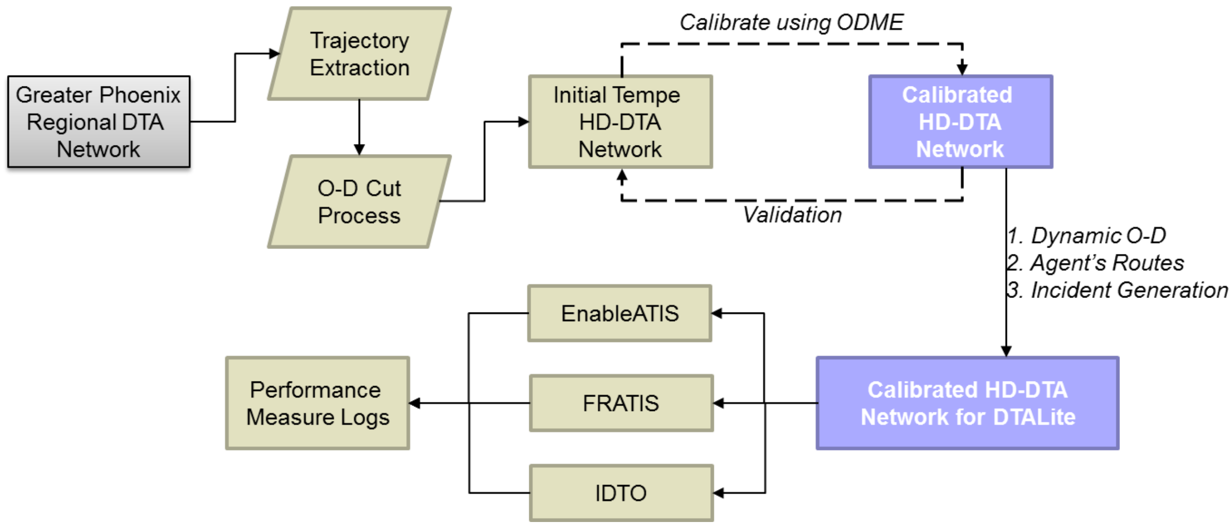


Figure 3-6: Phoenix Testbed Modeling Framework and Components [Source: Booz Allen]

3.3 Evaluation Baseline

This section explains the baseline calibration conditions upon which DMA applications are operated and scenarios are compared. For details on the use of cluster analysis to identify operational conditions and baseline calibration, readers are encouraged to refer to the FHWA publications FHWA-JPO-16-377 and FHWA-JPO-16-379, for San Mateo and Phoenix respectively.

3.3.1 San Mateo

To evaluate the performance of applications, baseline scenarios are defined over four different operational conditions in terms of weather, incident severity, and demand conditions (Figure 3-7).

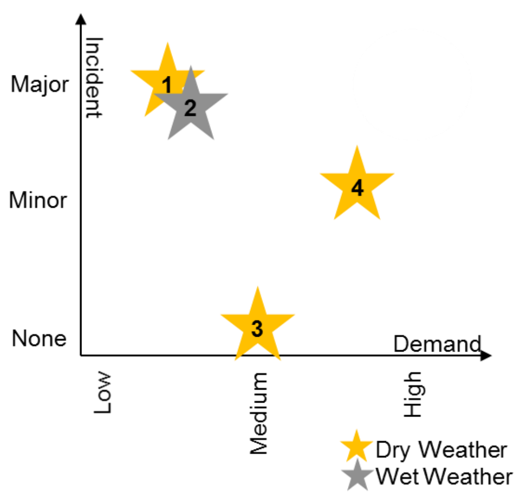


Figure 3-7: Operational Conditions for San Mateo [Source: Booz Allen]

Different operational conditions are used to represent the whole spectrum of traffic conditions for the evaluation of DMA applications and bundles. Each operational condition represents a specific combination of the following attributes: traffic demand level (low, medium, and high), weather condition (wet and dry), and incident occurrence (minor, major, and no incident). A normal operational condition is the one with a 50th percentile demand level on a dry day with no incidents. For ease of reference, each operational condition is given an abbreviation referring to their conditions (i.e., demand level, Low=L, Medium=M, and High=H; weather condition, Wet=W and Dry=D), and incident occurrence, Minor=L, Major=H, and No incident=N). For example, for the first operational condition, the conditions of “medium” demand and “high” incident severity has been abbreviated to MD-HI. (Unless stated by a “WW”, the operational conditions represent “dry” pavement conditions). Details of each of the operational conditions are defined in Table 3-1. Three of the operational conditions contain incidents and one of them refers to a wet weather condition. Table 3-2 shows the incident location, duration, and other severity factors for each of these operational conditions. Please note, these incidents are only a representative of the actual lane-closures in the field logged by California Highway Patrol in order to replicate the actual traffic characteristics for the selected representative days.

Table 3-1: San Mateo Operational Conditions

	MD-HI	*MD-HI-WW*	*MD-NI*	*HD-LI*
Representative Day	8/2/2012	4/10/2012	10/22/1012	9/19/2012
Operational Condition	Medium Demand + Major Incident	Medium Demand + Major Incident + Wet Weather	Medium Demand + No Incident	High Demand + Minor Incident
VMT	159,388	160,052	163,672	165,590
Weather Condition	Dry	Wet (0.01 in/hr)	Dry	Dry
Number of Incidents	1	3	0	1

Table 3-2: Incident Descriptions

Operational Condition	*Location*	*Lanes*	*Start Time*	*End Time*
MD-HI	US-101 NB (Between Whipple Ave and Woodside)	3 left lanes	5:30 pm	6:03 pm
MD-HI-WW	US-101 NB (Prior to Woodside Rd Exit)	1 left lane	5:28 pm	5:56 pm
	US-101 NB (Between Whipple Ave and Woodside Rd)	All 5 lanes	5:30 pm	5:36 pm
	US-101 NB (Between Holly St and Ralston Ave)	2 right lanes	3:59 pm	4:33 pm
HD-LI	US-101 NB (North of SR-92 Exit)	2 left lanes	5:39 pm	6:06 pm

The San Mateo testbed is simulated under each baseline operational condition without any application being implemented and different traffic measures including average travel time, speed, delay, and number of stops are calculated so that other test scenarios can be compared to the baseline. Simulations are defined for five hours of the afternoon peak period, in addition to one hour of warm-up time with 50 percent of the first hour demand. The five-hour peak period extends from 2:30 pm to 7:30 pm and the baseline results are shown on Figure 3-8 and Figure 3-9. Results were aggregated at 15-minute interval in these figures. The travel-time metrics define the distinct difference between the different operational conditions. As results show, traffic condition is better in MD-NI operational condition and worsens until HD-LI-DW operational condition in terms of lower average speed and higher average travel time. Planning Time Index (TTI) is the ratio of the travel time during the peak period to the time required to make the same trip at free-flow speeds and demonstrates the travel time reliability within the corridor. The worst TTI for the northbound corridor is for MD-HI-WW of 2.41.

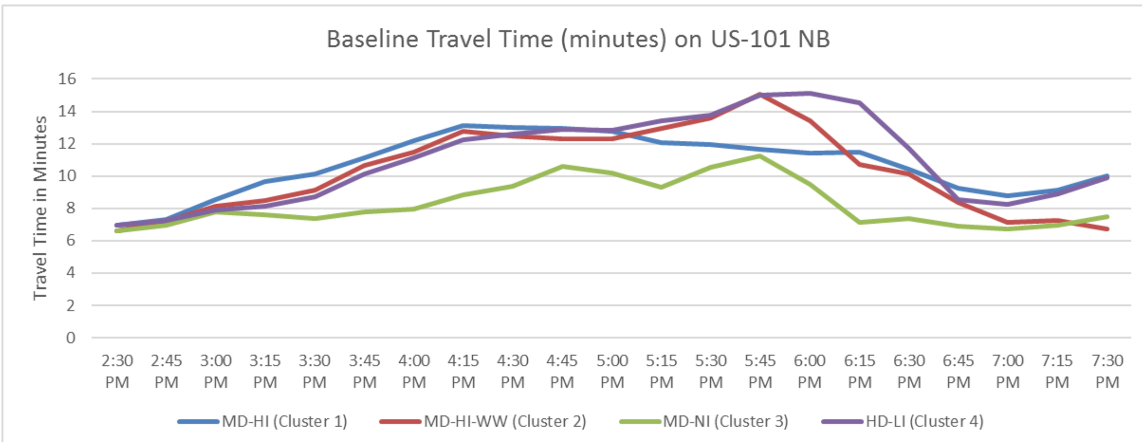


Figure 3-8: Baseline 15-minute US-101 NB Travel Time in San Mateo Testbed [Source: Booz Allen]

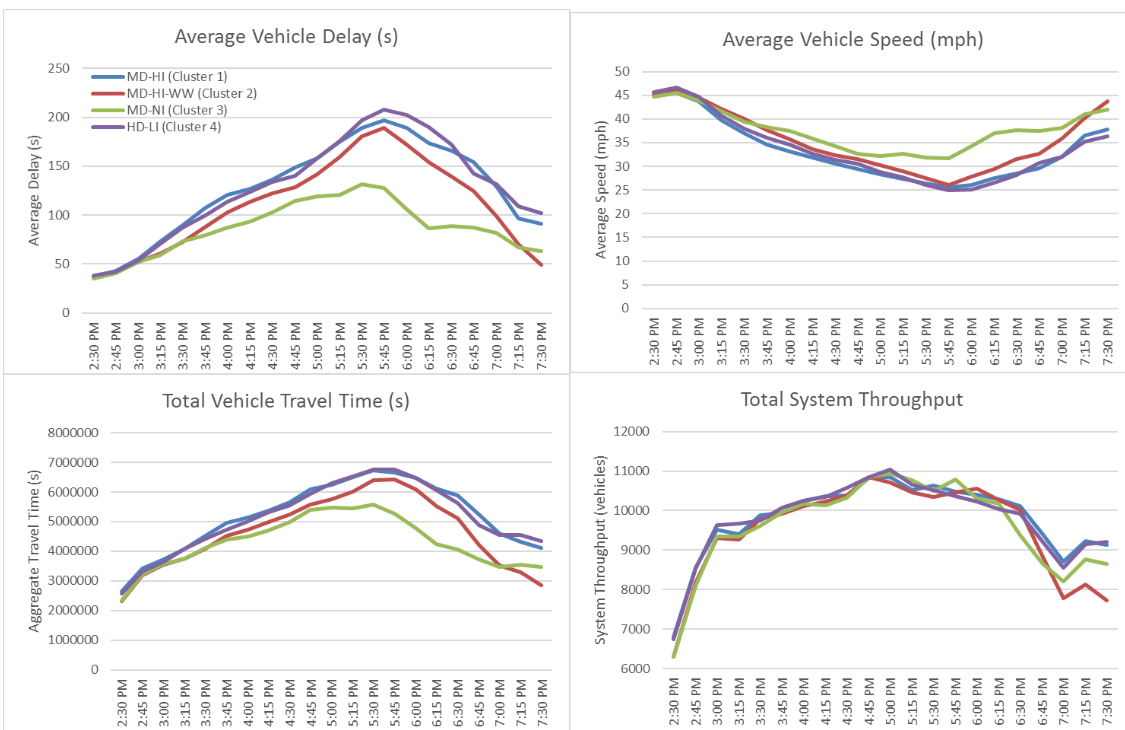


Figure 3-9: Baseline Performance Measures Between Different Operational Conditions [Source: Booz Allen]

3.3.2 Phoenix

For the Phoenix testbed, baseline scenarios are defined over four different operational conditions on to represent the whole spectrum of traffic conditions for the evaluation of DMA applications. Each operational condition represents a bin of multiple days in the analysis year and one representative day was selected for each operational condition that is closest to the centroid. The four different scenarios are defined over the afternoon peak hours of 3:00 pm to 7:00 pm, as shown in Table 3-3. The operational conditions are named based on the representative values of traffic demand, travel speeds, incident severity, and weather conditions. The traffic demand is represented by the average hourly volume in the network. The travel-speed is represented by the average speed of vehicles on the freeways in miles per hour and incident severity is represented by the product of number of incidents and the number of lane closures resulted from it. For example, operational condition 1 consists of higher traffic volumes, higher vehicle speeds, and low number of incidents and is therefore abbreviated as HD-LI (for high demand and low incident severity). The location of incidents is of extreme importance in modeling and is computed using the data patterns (loop-detector data) from freeways. Operational conditions 1 through 3 represent dry weather conditions, while Operational condition 4 is associated with wet pavement (or rain at 0.01 in/hour).

Table 3-3: Phoenix Operational Conditions

	HD-LI	***HD-HI***	***LD-LI***	***HD-MI-WW***
Representative Day	7/17/2014	5/21/2014	6/29/1014	11/22/2013
Operational Condition	High Traffic + High Speed + Low Incidents	High Traffic + High Speed + High Incidents	Low Traffic + High Speed + Low Incidents	High Traffic + Low Speed + Medium Incidents + Wet
Avg. Volume (veh/hr)	8383	8782	6004	7708
Avg. Speed (mph)	65	65.4	65.4	38.4
Weather Condition	Dry	Dry	Dry	Rainy (0.01 in/hour)
Number of Incidents*Lane Closure	9	22	3	23

The four representative days are chosen according to the Euclidean distances of samples away from the centroid values with each operational conditions. Only the afternoon attributes were used to calculate the Euclidean distances. For further details on the operational conditions, please refer to the testbed-specific calibration report.

Figure **3-10** shows a comparison of the baseline travel-time across the network for different operational conditions between 3:00 pm and 7:00 pm averaged at 15-minutes interval.

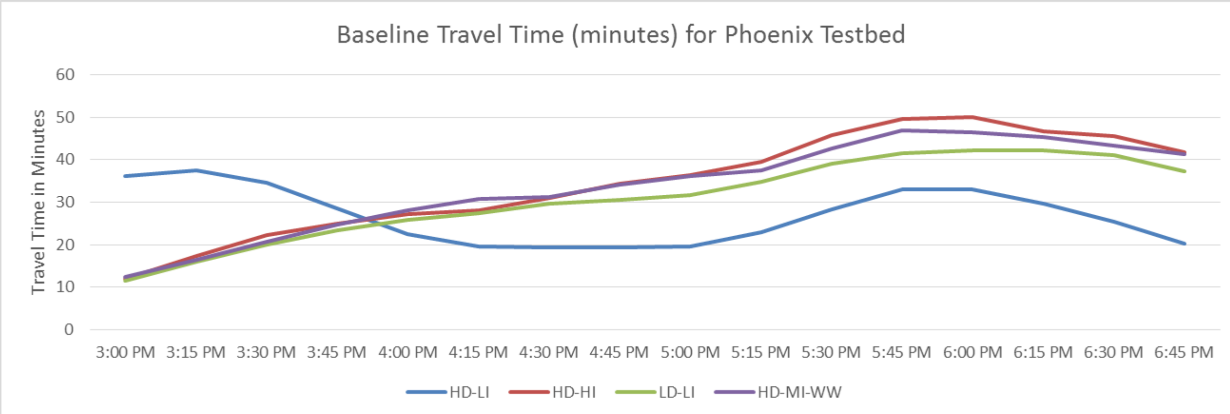


Figure 3-10: Comparison of Baseline Travel Time for Different Operational Conditions [Source: ASU]

3.4 DMA Research Questions

This section summarizes DMA research questions and their mapping to the testbeds that were used to examine each of those. The research questions are broadly divided into 10 categories and the major findings for each of these categories are given in later chapters. Please note that this mapping does not consider the San Diego testbed since it was a modification to this project. This section will be updated once San Diego analysis is finished. As shown in Table 3-4, a majority of research questions are answered by at least one of the testbeds. The research questions in the prediction and active management category were beyond the budgeted scope of this project. The project also did not address the questions in the policy category since modeling was not a good method to quantify them.

Table 3-4: DMA Research Questions Mapped to San Mateo and Phoenix Testbeds

ID	DMA Research Question	San Mateo	Phoenix
	Connected Vehicle Technology vs Legacy Systems		
1	Will DMA applications yield higher cost-effective gains in system efficiency and individual mobility, while reducing negative environmental impacts and safety risks, with wirelessly-connected vehicles, infrastructure, and travelers' mobile devices than with legacy systems? What is the marginal benefit if data from connected vehicle technology are augmented with data from legacy systems? What is the marginal benefit if data from legacy systems are augmented with data from connected vehicle technology?	●	
	Synergies and Conflicts		
2	Are the DMA applications and bundles more beneficial when implemented in isolation or in combination?	●	●
3	What DMA applications, bundles, or combinations of bundles complement or conflict with each other?	●	●

ID	DMA Research Question	San Mateo	Phoenix
4	Where can shared costs or cost-effective combinations be identified?		
5	What are the tradeoffs between deployment costs and benefits for specific DMA bundles and combinations of bundles?	●	
	Operational Conditions, Modes and facility Types		
6	What DMA bundles or combinations of bundles yield the most benefits for specific operational conditions?	●	●
7	Under what operational conditions are specific bundles the most beneficial?	●	●
8	Under what operational conditions do particular combinations of DMA bundles conflict with each other?	●	●
9	Which DMA bundle or combinations of bundles will be most beneficial for certain modes and under what operational conditions?		●
10	Which DMA bundle or combinations of bundles will be most beneficial for certain facility types (freeway, transit, arterial) and under what operational conditions?	●	●
11	Which DMA bundle or combinations of bundles will have the most benefits for individual facilities versus system-wide deployment versus region-wide deployment and under what operational conditions?	●	
12	Are the benefits or negative impacts from these bundles or combinations of bundles disproportionately distributed by facility, mode, or other sub-element of the network under specific operational conditions?	●	●
	Messaging Protocols		
13	Is SAE J2735 BSM Part 1 transmitted via Dedicated Short Range Communications (DSRC) every 10th of a second critical for the effectiveness of the DMA bundles? Will alternate messaging protocols, such as Probe Data Message (PDM), Basic Mobility Messages (BMM), etc., suffice? Given a set of specific messages, what combinations of bundles have the most benefit? Conversely, given a specific combination of bundles, what messages best support this combination?	●	●
14	To what extent are messaging by pedestrians, pre-trip, and en-route (e.g., transit riders) travelers critical to the impact of individual bundles or combinations of bundles? Does this criticality vary by operational condition?		●
	Communications Technology		
15	Will a nomadic device that is capable of communicating via both DSRC as well as cellular meet the needs of the DMA bundles? When is DSRC needed and when will cellular suffice?	●	●
	Communication Latency and Errors		

ID	DMA Research Question	San Mateo	Phoenix
16	What are the impacts of communication latency on benefits?	●	
17	How effective are the DMA bundles when there are errors or loss in communication?	●	
	RSE/DSRC Footprint		
18	What are the benefits of widespread deployment of DSRC-based RSEs compared with ubiquitous cellular coverage?	●	
19	Which technology or combination of technologies best supports the DMA bundles in terms of benefit-cost analysis?		
	Prediction and Active Management Investment		
20	Can new applications that yield transformative benefits be deployed without a commensurate investment in prediction and active management (reduced control latency)? How cost-effective are DMA bundles when coupled with prediction and active management?		
	Deployment Readiness		
21	To what extent are connected vehicle data beyond BSM Part 1 instrumental to realizing a near-term implementation of DMA applications? What specific vehicle data are the most critical, and under what operational conditions?	●	
22	At what levels of market penetration of connected vehicle technology do the DMA bundles (collectively or independently) become effective?	●	●
23	What are the impacts of future deployments of the DMA bundles in the near, mid, and long term (varying market penetration, RSE deployment density, and other connected vehicle assumptions)?	●	●
	Policy		
24	In simulating different policy conditions (such as availability of PII versus no PII), what are the operational implications? For example, what are the incremental values to certain applications of knowing travel itineraries in real-time versus with some delay (i.e., 1-5 minutes)?		
25	To what level are applications dependent upon agency/entity participation to deliver optimal results? What happens to the effectiveness of an application if, for example, local agency participation varies within a regional deployment?		
26	What are the variations if an application is set up to deliver system-optimal results versus user-optimal results? At what level of user “opt-in” does an application succeed/fail to deliver anticipated benefits, particularly to offset costs, if costs are associated with it?		

ID	DMA Research Question	San Mateo	Phoenix
27	How sensitive are individual applications to the availability (or lack thereof) of data from multiple sources/agencies?		
28	What types of data are necessary from non-transportation entities (for instance, hospitals or weather)? What data, and/or levels of participation by these entities would be required/optimal?		
29	What are the benefits to participants versus non-participants?		

3.5 DMA Hypotheses

This section outlines the preliminary hypothesis used to assess different research questions identified for the AMS Project[23]. These are shown in Table 3-5.

Table 3-5: DMA Research Question Analysis Hypothesis

ID	DMA Research Question	Analysis Hypotheses
1	Will DMA applications yield higher cost-effective gains in system efficiency and individual mobility, while reducing negative environmental impacts and safety risks, with wirelessly-connected vehicles, infrastructure, and travelers' mobile devices than with legacy systems? What is the marginal benefit if data from connected vehicle technology are augmented with data from legacy systems? What is the marginal benefit if data from legacy systems are augmented with data from connected vehicle technology?	Compared to legacy systems, DMA applications that make use of new forms of wirelessly-connected vehicle, infrastructure, and mobile device data will yield cost-effective gains in system efficiency and individual mobility, while reducing negative environmental impacts and safety risks.
2	Are the DMA applications and bundles more beneficial when implemented in isolation or in combination?	Applications which act on different facility types are more likely to be synergetic. For example, INFLO works on freeways and MMITSS works on arterials. Together, they can improve overall mobility.
3	What DMA applications, bundles, or combinations of bundles complement or conflict with each other?	Applications which act on similar facility types and provide similar types of advisories to drivers are more likely to be conflicting. For example, INFLO and INC-ZONE acts on

[23] Vasudevan and Wunderlich, Analysis, Modeling, and Simulation (AMS) Testbed Preliminary Evaluation Plan for Dynamic Mobility Applications (DMA) Program, FHWA-JPO-13-097

ID	DMA Research Question	Analysis Hypotheses
		vehicles that are on a freeway through "speed recommendations". These could be conflicting.
4	Where can shared costs or cost-effective combinations be identified?	Bundles that are highly synergistic will have shared connected vehicle technology deployment costs. This is not covered in the current evaluation.
5	What are the tradeoffs between deployment costs and benefits for specific DMA bundles and combinations of bundles?	Incremental increase in deployment will result in higher benefit-cost ratio up to a certain deployment cost threshold, after which benefit-cost ratio will reduce.
6	What DMA bundles or combinations of bundles yield the most benefits for specific operational conditions?	Certain DMA bundles or combinations of bundles will yield the highest benefits under specific operational conditions. For example, a combination of R.E.S.C.U.M.E and EnableATIS will have greater impact on days with high-demand and incidents than a combination of FRATIS and EnableATIS.
7	Under what operational conditions are specific bundles the most beneficial?	A DMA bundle will yield the highest benefits only under certain operational conditions. For example, on non-incident days, R.E.S.C.U.M.E. will have limited impact.
8	Under what operational conditions do particular combinations of DMA bundles conflict with each other?	Certain combinations of bundles will conflict with each other under specific operational conditions, resulting in no benefits or reduced benefits. For example, under high traffic, INC-ZONE application may not give any benefit since there is not much room for improvement.
9	Which DMA bundle or combinations of bundles will be most beneficial for certain modes and under what operational conditions?	Certain DMA bundles or combinations of bundles will yield the highest benefits for specific modes and under certain operational conditions. For example, FRATIS applications provide large benefits to freight vehicles.
10	Which DMA bundle or combinations of bundles will be most beneficial for certain facility types (freeway, transit, arterial) and under what operational conditions?	Certain DMA bundles or combinations of bundles will yield the highest benefits for specific facility types and under certain operational conditions. For example, MMITSS application is an arterial application and aims at improving arterial mobility.
11	Which DMA bundle or combinations of bundles will have the most benefits for individual facilities versus system-wide deployment versus region-wide deployment and under what operational conditions?	Certain synergistic DMA bundles will yield the most benefits when deployed together on individual facilities rather than as system-wide or region-wide deployments and under certain operational conditions and vice versa.
12	Are the benefits or negative impacts from these bundles or combinations of bundles disproportionately distributed by facility, mode, or other sub-element of the network under specific operational conditions?	Benefits or negative impacts from bundles will be unevenly distributed by facility, mode, or other sub-element of the network. For example. INFLO benefits might solely on freeways and not on arterials.

ID	DMA Research Question	Analysis Hypotheses
13	Is SAE J2735 BSM Part 1 transmitted via Dedicated Short Range Communications (DSRC) every 10th of a second critical for the effectiveness of the DMA bundles? Will alternate messaging protocols, such as Probe Data Message (PDM), Basic Mobility Messages (BMM), etc., suffice? Given a set of specific messages, what combinations of bundles have the most benefit? Conversely, given a specific combination of bundles, what messages best support this combination?	BSM Part 1 data transmitted every 10th of a second via DSRC is not critical for the effectiveness of DMA applications, with the exception of CACC. DMA bundles will be more effective with alternate messaging protocols in addition to BSM Part 1.
14	To what extent are messaging by pedestrians, pre-trip, and en route (e.g., transit riders) travelers critical to the impact of individual bundles or combinations of bundles? Does this criticality vary by operational condition?	Bundles that most significantly influence or are impacted by travelers' trip making decisions (EnableATIS, IDTO) or pedestrian movements (MMITSS, R.E.S.C.U.M.E.) will have the most critical need for messaging by pedestrians, and pre-trip and en route travelers. This criticality will vary by operational condition. This is not covered in the current evaluation plan.
15	Will a nomadic device that is capable of communicating via both DSRC as well as cellular meet the needs of the DMA bundles? When is DSRC needed and when will cellular suffice?	Nomadic devices that are capable of communicating via both DSRC as well as cellular will meet most of the needs of the DMA applications; however, additional data from the infrastructure will be required for DMA applications to be effective. DMA applications, with the exception of component applications of the INFLO and MMITSS bundles, will not need data to be transmitted via DSRC as higher-latency communications media (e.g., cellular) will suffice. This is not covered in the current evaluation plan.
16	What are the impacts of communication latency on benefits?	As communication latency increases, benefits will decrease. Most significant decrease will be observed for MMITSS and INFLO than for the other bundles.
17	How effective are the DMA bundles when there are errors or loss in communication?	Effectiveness of some DMA bundles will be more impacted than others due to errors or loss in communication. MMITSS and INLFO will be most impacted by errors or loss in communication.
18	What are the benefits of widespread deployment of DSRC-based RSEs compared with ubiquitous cellular coverage?	In comparison to widespread cellular coverage, widespread deployment of DSRC-based RSEs will be excessive for DMA bundles. Concentrated deployment of DSRC-based RSEs will be more cost-beneficial in highly congested urban areas than in non-urban or low to moderate congested urban areas.
19	Which technology or combination of technologies best supports the DMA bundles in terms of benefit-cost analysis?	More cost-effective benefits will be observed when connected vehicles transmit and receive messages using

ID	DMA Research Question	Analysis Hypotheses
		dual mode communications (e.g., both DSRC and cellular). This is not covered in the current evaluation plan.
20	Can new applications that yield transformative benefits be deployed without a commensurate investment in prediction and active management (reduced control latency)? How cost-effective are DMA bundles when coupled with prediction and active management?	DMA bundles (individually and in combination) will be more cost-effective only when coupled with prediction and active management.
21	To what extent are connected vehicle data beyond BSM Part 1 instrumental to realizing a near-term implementation of DMA applications? What specific vehicle data are the most critical, and under what operational conditions?	BSM Part 1 sent via DSRC is critical only to CACC; however other DMA applications will also need some elements of BSM Part 1 (i.e., position, speed, and acceleration) to be effective even in the near term. This is valid for all operational conditions.
22	At what levels of market penetration of connected vehicle technology do the DMA bundles (collectively or independently) become effective?	Benefits will increase with increase in market penetration of connected vehicle technology; some bundles will yield significant benefits even at lower market penetration levels.
23	What are the impacts of future deployments of the DMA bundles in the near, mid, and long term (varying market penetration, RSE deployment density, and other connected vehicle assumptions)?	Bundles that influence traveler decision-making and leverage widely deployed mobile device technology, such as EnableATIS, FRATIS, and IDTO, will yield measureable but geographically diffused system-level impacts under near-term deployment assumptions. Bundles that influence tactical driver decision-making and depend on emerging localized low-latency messaging concepts, e.g., MMITSS, Q-WARN and SPD-HARM, will yield measureable localized benefits in urban areas under near-term deployment assumptions, but limited system-level impacts until market penetration of connected vehicle technology reaches bundle-specific thresholds. This is not covered in the current evaluation plan.
24	In simulating different policy conditions (such as availability of PII versus no PII), what are the operational implications? For example, what are the incremental values to certain applications of knowing travel itineraries in real-time versus with some delay (i.e., 1-5 minutes)?	Effectiveness of some DMA bundles will be more impacted than others due to availability of PII. Bundles that influence traveler decision-making, such as EnableATIS, FRATIS, and IDTO, will be most impacted with availability of PII versus no PII. This is not covered in the current evaluation plan.
25	To what level are applications dependent upon agency/entity participation to deliver optimal results? What happens to the effectiveness of an application if, for example, local agency	Effectiveness of DMA bundles will be impacted by the lack of participation by local agencies/entities. Effectiveness of DMA bundles will be impacted by the lack of multi-source data from different agencies. Effectiveness of DMA bundles cannot be examined to the full extent without

ID	DMA Research Question	Analysis Hypotheses
	participation varies within a regional deployment?	some data from non-transportation entities (e.g., weather data). This is not covered in the current evaluation plan.
26	What are the variations if an application is set up to deliver system-optimal results versus user-optimal results? At what level of user "opt-in" does an application succeed/fail to deliver anticipated benefits, particularly to offset costs, if costs are associated with it?	Only some applications such as EnableATIS, IDTO etc. can be set up to deliver results in either system-optimal way or user-optimal way. Such DMA applications would have a trade-off between the optimization audience and the benefits achieved.
27	How sensitive are individual applications to the availability (or lack thereof) of data from multiple sources/agencies?	IDTO will be beneficial only with data from various transit agencies; FRATIS will be beneficial when there is data from freight companies and terminal operators; EnableATIS also relies on multiple sources of data including traffic and transit.
28	What types of data are necessary from non-transportation entities (for instance, hospitals or weather)? What data, and/or levels of participation by these entities would be required/optimal?	Non-transportation entities do not contribute much to DMA applications and therefore the impact of lack of non-transportation data would be marginal.
29	What are the benefits to participants versus non-participants?	Application participants will receive more benefits when compared to non-participants at lower market penetration. As market penetration increases, this gap will reduce.

3.6 Key Performance Measures

This section describes the key performance measures to be generated specifically to address the hypothesis. The performance measures should provide an understanding of travel conditions in the study area; and demonstrate the ability of DMA applications to improve corridor or system mobility, throughput, and reliability based on current and future conditions. These performance measures have been developed in coordination with the USDOT's DMA program evaluation team. In addition to looking at assessing the overall performance of the network, performance measures are proposed specific to each DMA bundle to match individual bundle's goals and objectives.

3.6.1 Overall Performance Measures

Performance measures are identified across the applications that will be used to assess individual application impacts in the testbeds under different operational conditions. Since DMA applications are primarily working towards mobility improvements using connected vehicles, performance measures focusing on mobility would be considered universal across the different applications and bundles. Some of the overall performance measures are given below:

1. Average Travel Speed: Average speed of vehicles is computed based on individual vehicle's average spot speeds over the entire operational period.

2. Average Delay of Vehicles: Vehicle delay is computed as the deviation in individual vehicle's travel-time during the simulation from its anticipated travel-time during free flow conditions. This delay would be averaged for all vehicles in the simulation to derive average delay.
3. System Throughput: This represents the average number of vehicles served in a given simulation time and is computed based on latent demand at the end of simulation.
4. Planning Time Index: This measures the travel-time reliability under different operational conditions and is defined as the ratio of the peak-period travel-time as compared to the free-flow travel time[24]. For simulation cases, free-flow travel time is computed as the travel time of vehicles during the warm-up period, which represents 50 percent volume.

Overall performance measures are identified so that the evaluation of DMA application combinations and DMA bundles can be done as part of the evaluation.

3.6.2 Application-specific Performance Measures

The overall performance measures discussed in previous section are aggregate for the entire region and hence may be insignificant to demonstrate the impact of DMA applications which are localized. Therefore, application-specific performance measures are defined to demonstrate impact of specific applications. These additional performance measures are given:

EnableATIS

1. Average Travel Time: The average vehicle travel-time is computed based on individual vehicle's travel-time and is compared against different operational conditions.
2. Average Travel Distance: The average travel distance in miles is computed based on the individual vehicle's trip distance.

INFLO

1. Reduction in Speed Variation: This is computed as the average reduction in the difference between the 95th percentile spot speeds within a sublink in adjacent time-periods. A sublink is defined as a 0.5-mile long subsection of a freeway.
2. Reduction in Shockwaves: This is computed as the average reduction in the difference between 95th percentile spot speeds between adjacent sublinks in the same time-period.

MMITSS

1. Average Arterial Travel Time: This measure is defined as the average travel time of a through vehicle in the arterial segment with an MMITSS intersection.
2. Maximum Queue Length: Maximum queue length at an intersection approach is used to assess the performance of I-SIG.

IDTO

1. Transit Travel Time Savings: The average travel time saved by transit travelers using IDTO.
2. Average Reduction in Vehicles: The average number of vehicles required to serve the same number of SOV travelers due to D-RIDE.

FRATIS

1. Truck Travel-time: This is the time taken by multi-destination trucks to complete trips. The FRATIS application modeled in this project assumes that trucks with multiple stops optimize their routes and order of waypoints according to current traffic conditions.

[24] FHWA Office of Operations, Planning Time Index Definitions, Accessed at http://www.ops.fhwa.dot.gov/publications/tt_reliability/ttr_report.htm#buffer

R.E.S.C.U.M.E.

1. Average Speed of Vehicles: Average speed of vehicles around the incident is an indirect safety measure in minimizing incident-zone personnel fatalities.
2. Increase in Incident Throughput: Incident throughput is defined as the number of vehicles that pass the incident zone in a given duration and is a mobility measure.

Table 3-6 shows a mapping of testbed performance measures and includes both application-specific and overall performance measures.

Table 3-6: Mapping of DMA-based Performance Measures with Testbeds

Performance Measure	San Mateo	Phoenix
Average Travel Speed	X	X
Average Vehicle Delay	X	X
System Throughput	X	X
Planning Time Index	X	X
Average Travel Time		X
Average Travel Distance		X
Reduction in Speed Variation	X	
Reduction in Shockwaves	X	
Arterial Travel Time	X	
Maximum Intersection Queue Length	X	
Transit Travel Time		X
Reduction in SOV Vehicles		X
Overall Truck Travel-time		X
Average Incident Zone Speed	X	X
Incident Zone Throughput	X	X

Chapter 4. Connected Vehicles and Legacy Systems

This chapter deals with the research findings regarding the benefits of using connected vehicle and legacy system data. It looks into the marginal benefits that are obtained when we have data from both sources when compared to a single source. For this analysis, connected vehicle data refers to the instantaneous vehicle-specific speed, location, heading, and related data that is provided to the applications. Legacy system data represents the data from traditional sources, such as freeway loop-detectors and intersection detectors. This includes infrastructure-based systems that detect vehicles, such as loop detectors, RADAR-based systems, and systems that disseminate instructions back to vehicles (e.g., VMS, dynamic speed limits).

4.1 Research Questions and Hypotheses

The following research questions are answered using this analysis:

1. Will DMA applications yield higher cost-effective gains in system efficiency and individual mobility, while reducing negative environmental impacts and safety risks, with wirelessly-connected vehicles, infrastructure, and travelers' mobile devices than with legacy systems?
2. What is the marginal benefit if data from connected vehicle technology are augmented with data from legacy systems? What is the marginal benefit if data from legacy systems are augmented with data from connected vehicle technology?

The hypothesis is that compared to legacy systems, DMA applications that make use of new forms of wirelessly-connected vehicle, infrastructure, and mobile device data will yield cost-effective gains in system efficiency and individual mobility, while reducing negative environmental impacts and safety risks. In other words, connected vehicle data will significantly improve the performance of DMA applications.

4.2 Analysis Approach and Research Findings

Both the San Mateo and Phoenix testbeds were used to assess these questions based on the following applications: (1) INFLO; (2) MMITSS; and (3) EnableATIS.

Specifically, INFLO (which includes Q-WARN and SPD-HARM) was modeled with just CV data and a combination of CV data combined with legacy system data (from loop detectors). The INFLO application subscribes to two data sources –transportation sensor systems (TSS) data, such as data from loop detectors, and CV data to effectively develop harmonized speeds for different sections of the freeway. This assessment compares the influence and contribution of these data inputs to the overall performance of the application. Interested users are encouraged to refer to USDOT documents FHWA-JPO-14-169[25] and FHWA-JPO-15-213.[26]

Similarly, MMITSS uses both CV data and detector calls to generate optimized signal timings for the intersections. A preliminary assessment of the application's system design suggests that at lower market penetration, detector calls are required for effective system functioning. As more and more vehicles are instrumented, the application might be able to run with just CV data without compromising benefits. In this assessment, different levels of market penetration of MMITSS were modeled with both sources of data and with just CV data sources.

EnableATIS was also assessed using a combination of CV data, representing en-route dynamic routing, as well as legacy data, represented by pre-trip routing and VMS.

4.2.1 INFLO Assessment

Three cases were compared to assess the performance of INFLO when the application subscribes to specific data sources.

1. A "**baseline**" case was used to establish baseline performance measures and represented the case when INFLO is not used. The basic calibrated network for the MD-NI operational condition was used in the case of the San Mateo testbed to assess this. Under the baseline condition, there was recurring congestion on US-101 northbound near the SR-92 interchange starting from the Ralston Avenue ramps. For further description of the baseline, readers are encouraged to read San Mateo Testbed's Calibration Report (FHWA-JPO-16-377).
2. A "**CV data only**" case was simulated using the same testbed and operational conditions, but with INFLO running on US-101 northbound. The application subscribes to the data from the CV-equipped vehicles on the freeway to determine queues and harmonize speeds across different sublinks.
3. The third case, known as "**CV + detector data**" case, consisted of simulations similar to the previous case. However, the INFLO application, in this case, also subscribes to detector data from the instrumented infrastructure-based data collection units on the freeway. These data collection units are equipped at every 0.5 miles on the freeway to supplement the application with average speed, volume, and occupancy data. Please note that INFLO does not fuse the CV and detector data together, instead, just utilizes the lower representative value for each sub-link where CV and detector data is present.

The three cases were analyzed for a 5-hour simulation window representing afternoon peak traffic for a medium demand/no incident (MD-NI) operational condition and the results are shown in Figure 4-1. This operational condition was used to avoid the confounding effect of incident-related congestion and weather-related factors.

As shown in Figure 4-1, an INFLO assessment with three different levels of market penetration (10 percent, 25 percent, and 50 percent) and INFLO-specific performance measures, such as reduction in shockwaves and speed variations, were quantified. Each of these market penetrations were tested using

[25] Battelle, System Design Document for the INFLO Prototype, Accessed at : http://ntl.bts.gov/lib/54000/54800/54846/INFLO-System-Design-FINAL-508-compliant_FHWA-JPO-14-169.pdf

[26] Battelle, Technical Report on Prototype Intelligent Network Flow Optimization (INFLO) Dynamic Speed Harmonization and Queue Warning, Accessed at: http://ntl.bts.gov/lib/55000/55300/55304/100030614-601_Technical_Report_on_Prototype_Intelligent_Network_Flow_Optimization_Final_.pdf

five different random seeds and an average value is shown along with their trend-lines to reveal the overall direction of the data.

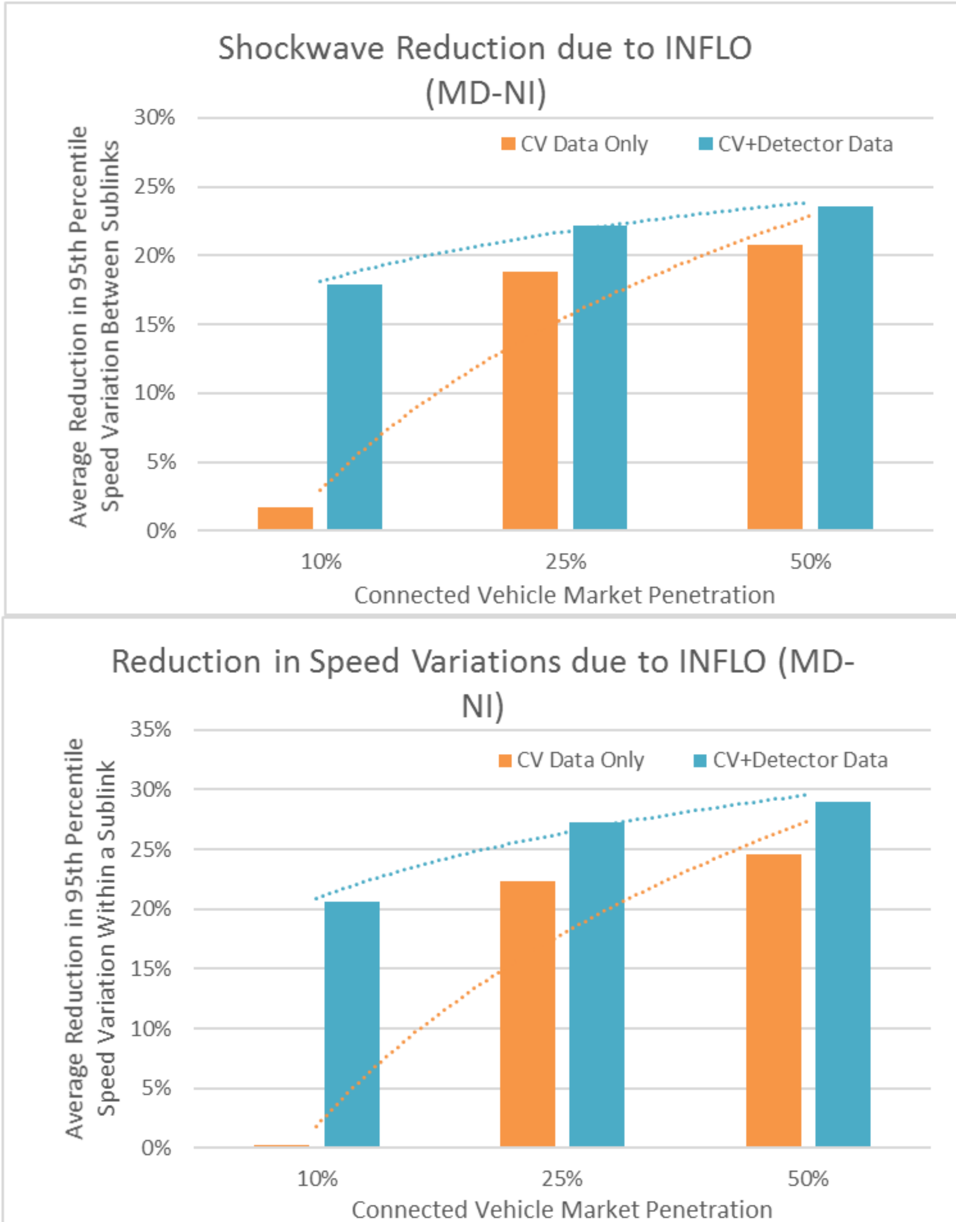


Figure 4-1: Performance of INFLO with and without Legacy System Data as Compared to Baseline [Source: Booz Allen]

Results indicate that at 10 percent market penetration, the reduction in shockwaves and speed variations were marginal when the application subscribed to only CV data. However, when CV data was supplemented with detector data, these reductions were significant. The shockwaves and speed variations showed a reduction of 17 percent to 20 percent. At higher market penetration, the difference between subscribing to single and multiple data sources were not very different. For example, at 50 percent market penetration, the “CV data only” case yielded nearly 21 percent reduction in shockwaves, whereas the “CV + detector data” case yielded 24 percent reduction. Similarly, the reduction in speed variations were 25 percent and 28 percent for the two cases “CV data only” and “CV + detector data” respectively when the CV market penetration was 50 percent. It was seen that at 25 percent or higher market penetration, the vehicles start behaving harmoniously since 1 in 4 vehicles constraints the movement of other vehicles in the mix, thereby improving the overall benefits.

There are significant contributions to the effectiveness of DMA applications from both legacy system data and CV data when assessed using a medium day-no incident operational condition. As the example for INFLO shows, at lower market penetration, most of the benefits from the application come from the legacy system data. This gap narrows down as CV market penetration increases. Overall performance of the application in terms of average delay or average travel speed of vehicles were negligible. This is due to the algorithm’s objective to normalizing the vehicle speeds along the corridor. The algorithm dynamically changes the “desired speed distribution” of vehicles to fall within 5 miles per hour range of the next sub-link. In essence, this logic distributes congestion across the corridor, rather than just at a section to prevent shockwaves. Hence the change in average delay and speed compared to baseline remains negligible.

4.2.2 INC-ZONE and RESP-STG Assessment

Applications under the R.E.S.C.U.M.E. bundle, namely INC-ZONE and RESP-STG, use connected vehicle data to generate alerts and warnings by design. INC-ZONE application uses CV data, such as position, speed, heading, to undergo threat assessment for the vehicles and emergency scene personnel and generate alerts, warnings, or advisories based on the vehicle’s distance from the incident. Similarly, RESP-STG uses V2V communication to guide responders to reach their destination faster and for staging their vehicle properly. Since both applications rely on CV data, they could not be assessed for cases where only legacy systems are available. In other words, these applications only use CV data.

4.2.3 MMITSS Assessment

MMITSS was also assessed under different market penetrations with both CV data and detector data. MMITSS typically uses CV data to supplement detector calls to the controllers by identifying connected vehicles when they approach the intersection. The location information from the CV data received by the MMITSS application is used to place advanced calls on the phases by mapping them to their approach direction as well as lanes. In order to assess the importance of CV data and conventional detector data, three scenarios were simulated and compared against each other under three levels of market penetration. They are:

1. A “**baseline**” scenario, where the MMITSS application is not simulated. The intersection controllers are coded as normal actuated controllers receiving detector calls which can be assumed as the “legacy data” case.
2. A “**CV only**” scenario, where MMITSS controls the intersection controllers and uses CV data to identify connected vehicles approaching the intersection. No detector data was used in this scenario.
3. A “**CV + detector calls**” scenario, where MMITSS was simulated using both CV data and detector call data.

Change in arterial travel time, averaged over northbound and southbound directions between El Camino Real’s MMITSS-enabled intersections, was used as the performance measure and the results are shown in Figure 4-2. The figure also shows the change in maximum queue length on side streets due to MMITSS. The arterial travel time represents the average travel time of vehicles traveling in the mainline El Camino Real.

As shown in Figure 4-2, at lower market penetration, the change in arterial travel time due to the "CV only" scenario is worse than the "CV + detector" scenario, except for travel time savings when there is 10 percent market penetration. For example, at 25 percent market penetration, the reduction in arterial travel time is only 1.5 percent when CV data is used, whereas when CV data was supplemented with detector calls, the reduction in average arterial travel time was 2.1 percent. However, at higher market penetration, CV data is able to potentially harvest all of the MMITSS benefits. For example, at 75 percent market penetration, the reduction in arterial travel time during "CV only" scenario is 2.4 percent when compared to the "CV + detector" scenario of 2.5 percent. This trend is clearer for the change in maximum queue length on the side streets. MMITSS significantly reduces the queue build-up on the side streets since connected vehicles are able to provide early calls for the application to issue max-off and similar commands to the intersection controller to be served faster.

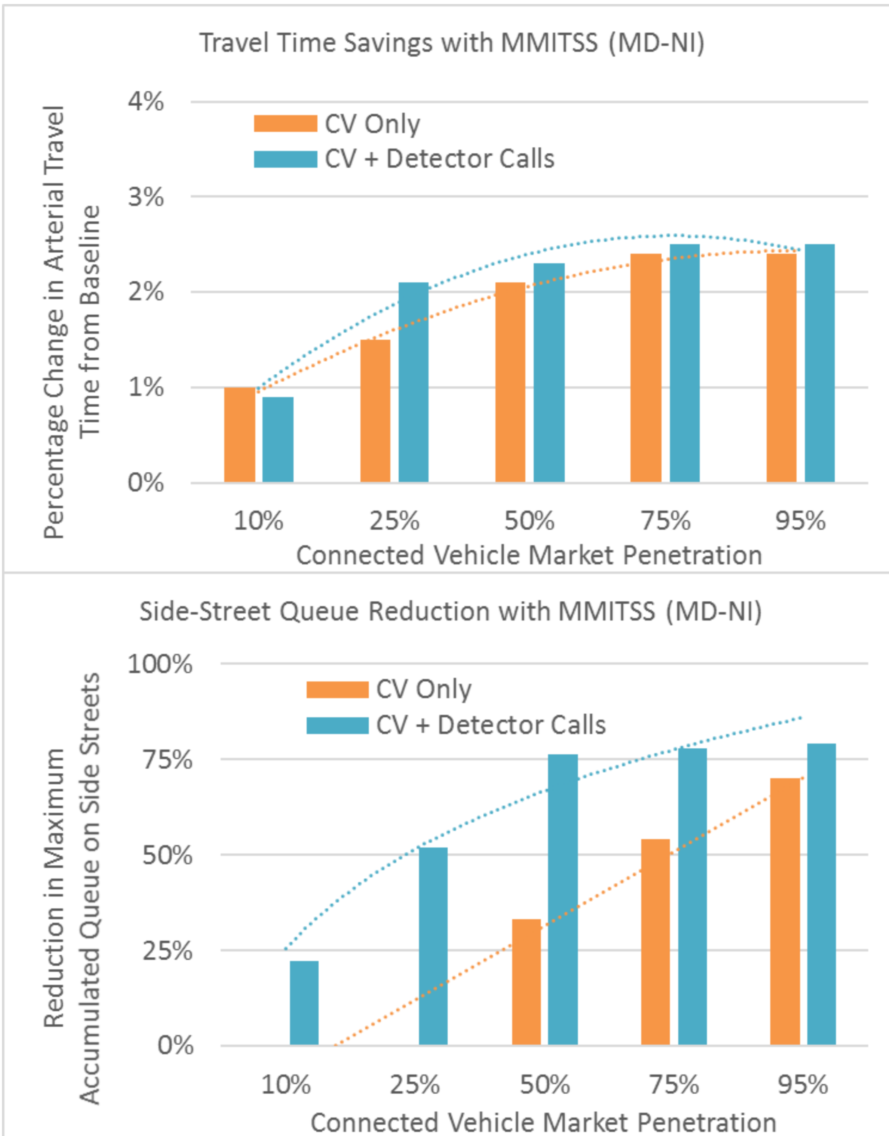


Figure 4-2: MMITSS Performance under Different Types of Data [Source: Booz Allen]

Chapter 6 demonstrates the performance of MMITSS (with both detector calls and CV data) under different levels of market penetrations for different operational conditions.

4.2.4 EnableATIS Assessment

Since EnableATIS is a strategic DMA application and works at a regional level, CV technology was assessed along with certain legacy systems. A full description of how EnableATIS models and changes travel behavior in the Phoenix testbed is provided in the Appendix F. Essentially, it utilizes the historic and real-time travel-time information to modify the route choice of drivers to optimize their travel time. Legacy systems are currently available and work without connected vehicle technology. Examples of legacy systems are VMS and pre-trip planning (based on routing and traffic conditions). Six scenarios are assessed for EnableATIS to analyze the contributions from legacy systems to enhance connected vehicle operations or vice versa (choose their routes prior to the trip based on traveler information available through traffic management centers).

1. Do Nothing case where no system is providing traveler information.
2. Test case where VMS are used to distribute traveler information across the network.
3. Test case where VMS messages are supplemented with 20 percent of travelers receiving pre-trip route information.
4. Test case where 50 percent of the travelers receive pre-trip route information. This case is used as the baseline for comparison.
5. Test case where 50 percent of the travelers choose their routes prior to their departure based on current traveler information and 20 percent of the travelers make en-route decisions based on real-time information using connected vehicle technology.
6. Test case where 50 percent of the travelers receive pre-trip information and 30 percent receive en-route information using CV technology.

The performance measures under these four cases in terms of average travel time and distance are shown in Figure 4-3. Please note that the case with 50% pre-trip is used as the baseline. As shown, the travel time reduces with more information (such as pre-trip planning and connected vehicle technology). However, pre-trip planning is shown to have a small decrease in the average travel distance since vehicles are rerouting based on traffic conditions and moving to non-optimal routes. Case four shows that this change in travel distance is less when CV technology is used in conjunction in pre-trip planning. This is because the connected vehicles have real-time information that enables them to optimize their route choice as traffic conditions change.

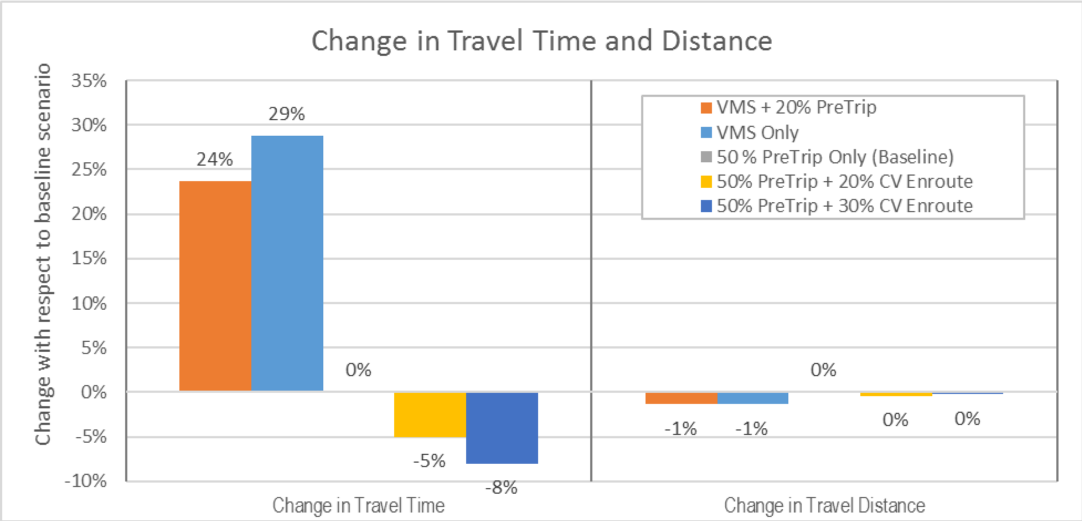


Figure 4-3: EnableATIS Performance under Legacy Systems and CV Technology [Source: Booz Allen]

For this question, we categorize VMS and pre-trip information as legacy systems (since they utilize traditional methods such as infrastructure-based messaging signs and 511 or similar systems) and en-route information as CV system-related benefits. As shown, there is a significant reduction in travel time, when legacy system data is used to provide advanced traveler information to travelers. There is only marginal benefit when legacy data is supplemented with CV data. Please note that this section shows the results under the high-demand, low incident severity operational condition. Other operational conditions are assessed in Chapter 6.

4.2.5 FRATIS Assessment

The FRATIS application was prototyped in the Phoenix testbed as a vehicle routing problem (VRP), where a set of truck origins and destinations are used to find the optimum paths and order of delivery destinations based on real-time traffic conditions on the links. The application was developed as a traffic assignment module within DTALite that uses the real-time traffic state from the network to find optimal route and destination order. In this sense, the application utilizes the link travel times from the network that, in real-life, are computed either using legacy system data or CV data. Since this input was not a configurable parameter in this application, this application was not addressed in this question.

4.2.6 IDTO Assessment

The two IDTO applications, T-DISP and D-RIDE, were developed and tested on the Phoenix testbed on a small scale. T-DISP was modeled as an application that allows transit agencies to use real-time link-specific travel time information to adjust transit routes and travelers to utilize multiple transit lines to reach their destination. This application relies on real-time connectivity between transit agencies and travelers and utilizes non-legacy technology. Similarly, D-RIDE utilizes real-time sharing of position and travel-requests from travelers and position and availability information from shared vehicles by utilizing connected vehicle/traveler technology. Since both these applications cannot work without connected vehicle/traveler technology, the marginal benefit of legacy systems or the lack of could not be assessed.

4.3 Results Summary

Certain DMA applications, such as INFLO, are designed to use connected vehicle and legacy system data. Legacy system data includes infrastructure-based data collection devices, such as loop detectors and video/radar detection systems. For the purpose of this evaluation, the team defines connected vehicle data as high-fidelity data from vehicles including position, speed, and heading. Legacy system data is defined as data from any infrastructure-based system to detect vehicles and disseminate instructions back to them.

Under lower market penetration, legacy system data are required for DMA applications, such as INFLO and MMITSS, to achieve benefits. As market penetration increases, these applications could rely entirely on connected vehicle data. The FRATIS and INC-ZONE applications relied completely on CV data. EnableATIS relied mostly on legacy data.

This analysis used simulations with different data inputs to the applications to assess whether DMA applications will yield benefits when legacy system data is supplemented or replaced with connected vehicle data. The results were application-specific. For INFLO and MMITSS, legacy system data contributes to most benefits at lower market penetration and CV data at higher market penetration.

Applications such as FRATIS and INC-ZONE (as implemented in this project) require CV data to work and hence were not evaluated for effectiveness under different data sources. EnableATIS relied mostly on legacy data and the addition of CV data caused marginal improvement in benefits.

The results indicate that at lower CV market penetration, DMA applications (such as INFLO and MMITSS) rely mostly on legacy system data to provide mobility benefits. However, as market penetration increases, this reliance can be replaced. For example, at 10 percent market penetration, INFLO provided only marginal reduction in shockwaves (less than 2 percent) when it subscribed to CV data only; whereas at 50 percent market penetration, this increased to 23 percent. However, when supplemented with data from legacy systems, INFLO reduced shockwaves by 21 percent even at 10 percent market penetration. A similar trend was shown by MMITSS. It was demonstrated that higher reductions in arterial travel time occurred when the application supplemented CV data with detector data, compared with CV data alone. Additionally, it was shown that MMITSS could work without legacy system data (detector calls) when the market penetration is higher. Compared to legacy systems, DMA applications (such as INFLO and MMITSS) that make use of new forms of wirelessly-connected vehicle, infrastructure, and mobile device data will yield cost-effective gains in system efficiency and individual mobility, when a higher percent of vehicles can wirelessly communicate with the DMA applications.

EnableATIS also demonstrated greater benefits when legacy data was supplemented with CV data in terms of travel time reduction. However, this improvement was marginal and legacy data contributed to most benefits.

Chapter 5. Synergies and Conflicts

This chapter documents the research findings regarding the synergies and conflicts among different DMA applications and bundles. It also refers to possible benefits in using the DMA applications and bundles in combination and isolation. In the San Mateo testbed, tactical DMA applications/bundles, such as INFLO, MMITSS, and INC-ZONE, are assessed and the strategic DMA applications, such as IDTO, FRATIS, and EnableATIS, are evaluated using the Phoenix testbed. While the synergies and conflicts between specific applications within the tactical and strategic groups were derived quantitatively using the established set of operational conditions, additional qualitative analysis was performed to assess the synergies and conflicts between two applications that fall under different groups. Primarily this involves a step-by-step assessment of the application, including the data requirement, data processing, and data dissemination. Please note that the strategic applications EnableATIS, IDTO, and FRATIS are targeted to different user groups and therefore a quantitative assessment of users using two or more of these applications was not performed. In addition, the team used the DMA National Impact Assessment model to develop a qualitative analysis on shared costs for different application combinations.

5.1 Research Questions and Hypotheses

The following research questions are answered using this analysis:

1. Are the DMA applications and bundles more beneficial when implemented in isolation or in combination?
2. What DMA applications, bundles, or combinations of bundles complement or conflict with each other?
3. Where can be shared costs or cost-effective combinations identified?
4. What are the tradeoffs between deployment costs and benefits for specific DMA bundles and combinations of bundles?

In order to analyze these questions, the following list of hypotheses was made:

1. DMA bundles that are synergistic will be more beneficial when implemented in combination than in isolation.
2. Certain DMA applications, bundles, or combinations of bundles will complement each other resulting in increased benefits, while others will conflict with each other resulting in no benefits or reduced benefits.
3. Bundles that are highly synergistic will have shared connected vehicle technology deployment costs.
4. Incremental deployment increases will result in higher benefit-cost ratios up to a certain deployment cost threshold, after which the benefit-cost ratio will reduce.

Questions 1 through 3 are answered in this chapter. In order to answer the questions on deployment costs versus benefits tradeoff, the team conducted an in-depth cost and benefits analysis. This is provided in Chapter 12.

5.2 Analysis Approach and Research Findings

The San Mateo testbed was used to model and simulate the INFLO, INC-ZONE, and MMITSS applications. Evaluating combinations of these applications requires a set of performance measures that is common across the different applications. Additionally, these applications are deployed over different geographic and temporal extents as follows:

1. INFLO is deployed only on US-101 Northbound between the Whipple Avenue junction and the SR-92 junction between 3:30 pm and 6:30 pm.
2. INC-ZONE is deployed within 1 mile upstream of incidents on US-101 northbound only for the duration of the incident.
3. MMITSS is deployed at the signalized intersections on SR-82 between the 43rd Avenue junction and the 20th Avenue junction.

The analyses of application combinations were performed using the Software-in-the-Loop set up described in Figure 3-3. Specifically, COM-based instances were used to control the INFLO and INC-ZONE behavior in the simulation and ASC/3 soft controllers were used to modify MMITSS-based signal commands. In order to run these applications in combination, the team used a simulation-manager approach which controls the simulation and derives the vehicle data at every time-step. The simulation manager then divides this data based on the type and location, and allocates it to individual applications. The application output is used to control specific elements of the simulation at the end of each time-step. The following table shows the control elements of each application so that there is no direct conflict in commands issued by the application manager.

Table 5-1. Simulation Control Elements of Different Applications

No.	Application	Control Elements
1	INFLO – SPD-HARM/Q-WARN	Link Desired Speed Distribution (@ 5 mph resolution)
2	R.E.S.C.U.M.E. – INC-ZONE	Vehicle Desired Speed Vehicle Desired Lane
3	MMITSS – I-SIG	Signal Controller Phases

5.2.1 Combination of INFLO and INC-ZONE

The INFLO and INC-ZONE combination was evaluated using the MD-HI operational condition denoting medium demand and high incident severity. Other operational conditions are given in Chapter 6. Four cases were assessed to make the comparison for three different levels of market penetration (10 percent, 25 percent, and 50 percent):

1. Baseline case where no application was simulated.
2. INC-ZONE case where INC-ZONE application will give speed-change and lane-change commands to equipped vehicles in the vicinity of incidents. INC-ZONE is set to work during the duration of the incident only.
3. INFLO case where the application will harmonize the speed across the freeway at 20-second frequency and 0.5-mile geographic interval. INFLO is set up to work between the hours of 3:30 pm and 6:30 pm.

4. Combination case where INFLO and INC-ZONE are used together. INFLO is set up to work throughout the US-101 NB (peak direction), between the hours of 3:30 pm and 6:30 pm and INC-ZONE is set up to be activated for any incident on the US-101 NB for the duration of the incident. Details on the incident for different operational conditions are given in Section 3.3.1.

Figure 5-1 below shows the performance of the test cases with respect to the baseline case for MD-HI operational condition under different levels of market penetration. The top two bar-plots show the INFLO-specific performance measures (reduction in shockwaves and speed variations) for the entire simulation time and the bottom two bar-plots shows the INC-ZONE specific performance measures (reduction in vehicle speeds at the incident zone and increase in the throughput of open-lanes) for the durations of the incidents. As shown, INFLO and INC-ZONE has a synergistic relationship under higher market penetration, implied by the fact that the performance measures of application combinations are better than individual applications. At lower penetration rates, however, INFLO does not benefit from having INC-ZONE. INC-ZONE is a localized application and at lower market penetration, lower vehicle ratio trying to adjust their speeds affects the overall “harmonization” of speed. Whereas when CV-penetration rate increases, more vehicles behave in similar (INC-ZONE defined) manner, thereby improving the “harmonization”.

Figure 5-1: Assessment of INFLO-INC-ZONE Combination for MD-HI Operational condition [Source: Booz Allen]

As shown in Figure 5-1, the reduction in shockwaves is 6 percent and 9.5 percent when INFLO application is used at 10 percent and 25 percent market penetration. This drops to 2.8 percent and 7.9 percent when combined with INC-ZONE application. However, for 50 percent market penetration, the shockwave reduction increases from 13.2 percent to 14.8 percent when INFLO is combined with INC-ZONE. Similar trends are shown for reduction in speed variation as well where at higher market penetrations the combination is yielding more benefits than the individual applications. This synergy is likely because INC-ZONE is providing vehicle-specific speed and lane commands within the incident zone to improve throughput by reducing the speeds of vehicles in a gradual manner.

As far as INC-ZONE performance measures are concerned, the speed of vehicles in an incident zone is reduced by up to 18 percent when 50 percent of vehicles have the INC-ZONE application. When combined with INFLO, this increases to nearly 28 percent. Since INFLO aims to harmonize vehicle speeds across the freeway, INFLO is helping INC-ZONE in its performance and vice-versa. Additionally, since INFLO is operational over the entire corridor, the vehicle speeds are already harmonized as they enter the incident zone and hence improving INC-ZONE's performance. Conclusively, INC-ZONE and INFLO applications are synergistic and are more beneficial in combination than isolation. These applications do not conflict with each other, since INFLO works at a sublink level INC-ZONE works at an individual vehicle level. INC-ZONE is localized to the incident zone and provides lane-level of advisory whereas INFLO works at a sublink level harmonizing the speed of the entire freeway corridor.

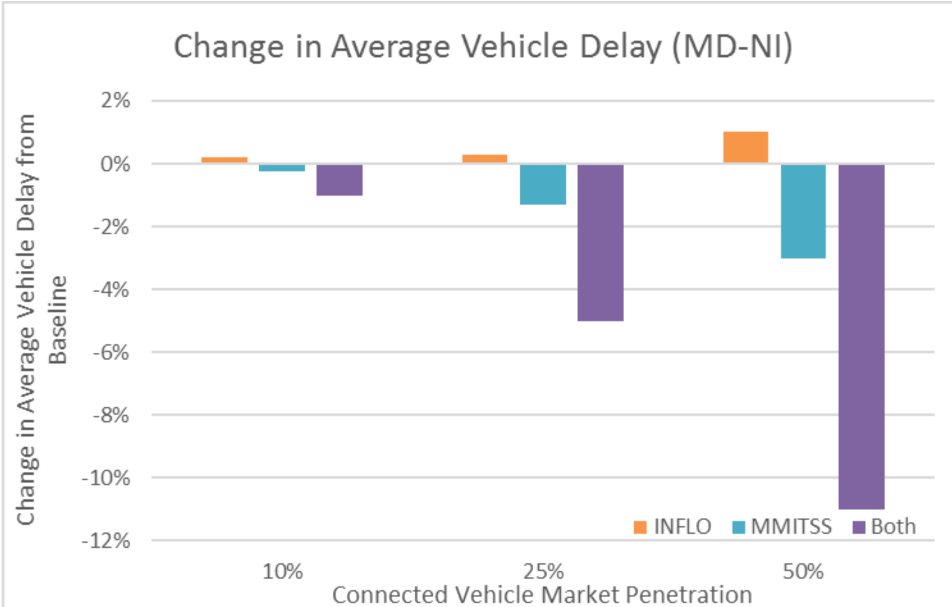
5.2.2 Combination of INFLO and MMITSS

INFLO and MMITSS applications run in different geographic areas. INFLO is a freeway-based application and MMITSS is an arterial-based application. In order to assess the impacts of the INFLO-MMITSS combination, overall performance measures in terms of average vehicle delay and average vehicle speed in the network was compared for three cases for the medium demand/no incident (MD-NI) operational condition. The results are provided below.

1. INFLO case where the application will harmonize the speed across the US-101 northbound freeway at 20-second frequency and 0.5-mile geographic interval. INFLO is set up to work between the hours of 3:30 pm to 6:30 pm.
2. MMITSS case where the northern-most eight signalized intersections on the El-Camino Real are controlled by the Intelligent Signal Control application.
3. INFLO+MMITSS case where both INFLO and MMITSS are working on their respective geographic limits.

Figure 5-2 below shows the performance of the three cases with respect to a MD-NI operational condition under different levels of market penetration, in terms of change in average vehicle delay and average vehicle speed. Both of these performance measures are measured for all vehicles in the simulation testbed for the entire duration of simulation. There is a synergistic relationship between the two applications and together they seem to improve the overall performance of the network.

As shown in Figure 5-2, the change in average vehicle delay due to INFLO and MMITSS in isolation was almost 0 percent at 10 percent market penetration; whereas there is a slight increase in delay (0.5 percent) due to 50% percent INFLO market penetration. The reduction in delay with 50 percent MMITSS market penetration was 3 percent. However, the combination yielded total reduction in delay of over 10.5 percent. This synergy is likely because the two applications together helped in optimizing vehicle movements across the two primary corridors of the testbed – El Camino Real arterial (MMITSS) and US101 freeway (INFLO). Similar results were also shown for the change in average speed. At 10 percent market penetration, the applications had insignificant impact on the average speed of vehicles, both in isolation and in combination. However, as the market penetration increased to 50 percent, the combination of applications improved the overall average speed of vehicles by 2 percent. In isolation, the change in average speed of vehicles due to INFLO was -0.8 percent and MMITSS was +1 percent.



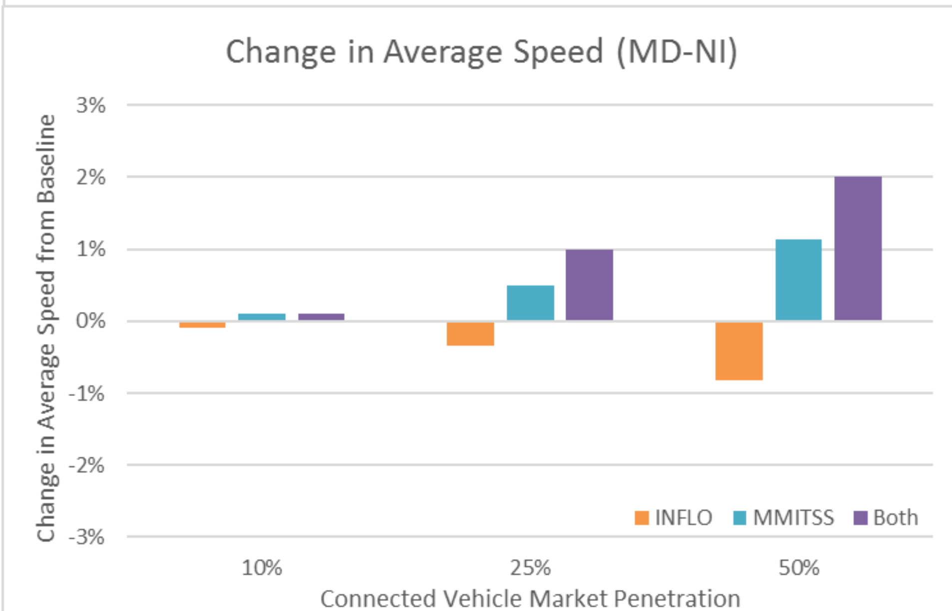


Figure 5-2: Assessment of INFLO- MMITSS Combination for MD-NI Operational condition [Source: Booz Allen]

5.2.3 Combination of MMITSS and INC-ZONE

Similar to the previous case, MMITSS and INC-ZONE work on different facility types. MMITSS was implemented on the eight signalized intersections towards the north of El Camino Real arterial and the INC-ZONE application was applied on freeway incident locations for a distance of 0.5 miles upstream of the incident. MMITSS focused on optimizing vehicle flow through the signalized arterial and INC-ZONE aimed at optimizing vehicle flow through the incident zones on the freeway by enhancing the throughput of open lanes. In order to assess the impacts of the MMITSS-INC-ZONE combination, overall performance measures in terms of average vehicle delay and average vehicle speed in the network was compared for three cases for the medium demand and high incident (MD-HI) operational condition as follows:

1. MMITSS case where the northern-most eight signalized intersections on the El-Camino Real are controlled by Intelligent Signal Control application.
2. INC-ZONE case where INC-ZONE application will give speed-change and lane-change commands to equipped vehicles in the vicinity of incidents. INC-ZONE is set to work during the duration of the incident only.
3. MMITSS+INC-ZONE case where both MMITSS and INC-ZONE applications are working on their respective geographic limits.

Figure 5-3 shows the performance of the three cases under different levels of market penetration in terms of change in average vehicle delay and average speed of vehicles. Both these performance measures are measured for all vehicles in the simulation testbed for the entire duration of simulation. There is a synergistic relationship between the two applications and together they seem to improve the overall performance of the network.

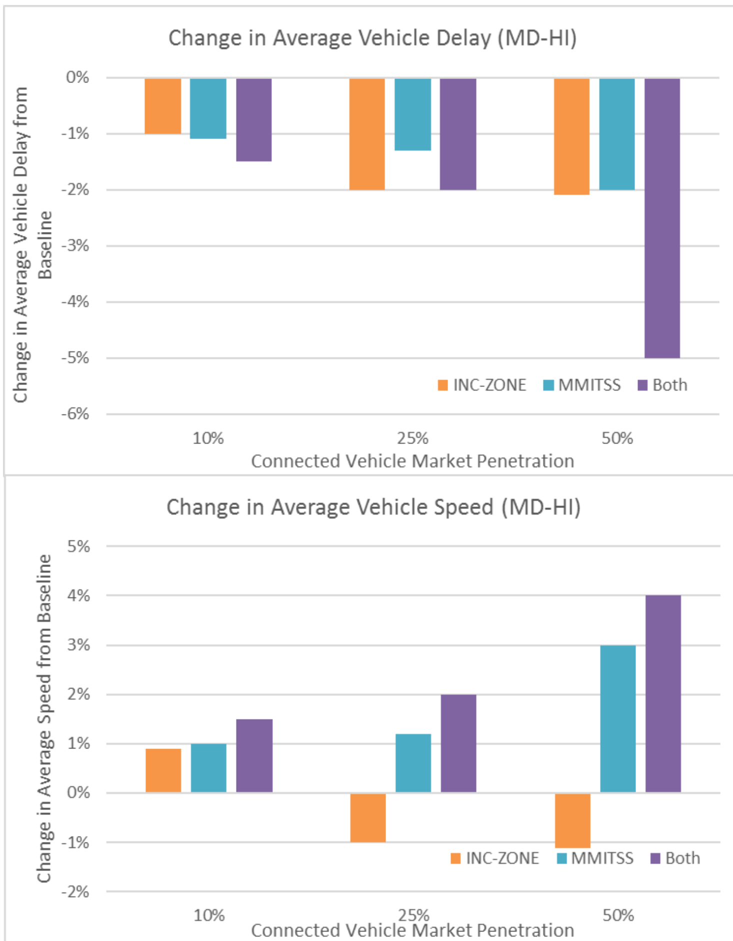


Figure 5-3: Assessment of INC-ZONE- MMITSS Combination for MD-HI Operational condition [Source: Booz Allen]

As shown in Figure 5-3, the change in average vehicle delay due to INC-ZONE and MMITSS in isolation is 0.9 percent and 1 percent respectively at 10 percent market penetration. However, in combination, they could reduce the average vehicle delay by up to 1.7 percent. This synergistic relationship improves as market penetration increases. In isolation, INC-ZONE and MMITSS applications reduce the average vehicle delay by 2 percent at 50 percent market penetration. But, in combination, the reduction in average delay is over 5 percent. This synergistic relationship is because the two applications together helped in optimizing vehicle movements across the two primary corridors of the testbed – El Camino Real arterial (MMITSS) and US-101 freeway (INC-ZONE). As far as the average speed of vehicles is concerned, this synergy is maintained with the combination improving the average speed more than either of the applications in isolation.

5.2.4 Qualitative Analysis of Other Combinations

In the previous sections, we used simulation-based results to assess the conflict and synergy between tactical DMA applications such as INFLO, INC-ZONE, and MMITSS. The strategic applications, such as EnableATIS, FRATIS, and IDTO, on the other hand, work at a traveler level and at disparate components of a transportation network. In order to assess their potential synergy and conflicts, we perform a qualitative analysis of these applications in this subsection by using the specific components of a transportation system that is affected by these applications. The following list provides specific information on each application and their potential impact on the transportation network.

1. The INFLO application, namely SPD-HARM and Q-WARN, uses information about sublink speeds and queued states at fixed geographic intervals on a freeway to modify the speed of vehicles in that sublink.
2. The INC-ZONE application in the R.E.S.C.U.M.E. bundle uses incident location and details on vehicles upstream of the incident to modify their desired lane and speed for the 0.5-mile length of travel.
3. The MMITSS application, especially I-SIG, utilizes the current signal phasing information and location of vehicles at each approach to modify the signal phasing that will reduce delays to vehicles.
4. EnableATIS uses the link travel times and the historic vehicle routes to optimize the route of vehicles for minimum delay in travel.
5. FRATIS uses the truck's origin and destination details as well as real time link travel times to optimize their routes for minimum travel delay.
6. The IDTO applications, namely T-DISP and D-RIDE, use transit passenger OD and departure/arrival windows to optimize dynamic transit routes/carpooling to reduce delay and the number of vehicles that would satisfy the traveler needs.

In order to track which applications conflict or synergize with each other, their primary and secondary output elements are mapped in the order of increasing resolution in Figure 5-4. As shown, the tactical applications primarily affect the driver-behavior parameters and the strategic applications affect the mode/route choice behavior. Therefore, no conflicting behavior is expected from combining a tactical and strategic application. For example, when the EnableATIS and INFLO applications are combined, the vehicle route is controlled by the EnableATIS application based on the travel-time on the links and the INFLO application adjusts the vehicle speeds on the selected link to reduce speed variations and shockwaves. As far as the combination of strategic applications, such as EnableATIS, IDTO, and FRATIS, are concerned, these applications work towards enhancing mobility of the overall network since they affect different types of users. As shown in the figure below, some of the applications will have secondary impacts and are not assessed in this project. For example, EnableATIS uses link travel-time to assign routes to travelers. However, the link travel-times might be affected by having applications such as MMITSS (which improves arterial travel-time) and INC-ZONE (which improves freeway travel-time in the event of an incident). Therefore, in the context of overall network-wide mobility, there might be a cyclic effect of some of these applications affecting others. For example, MMITSS improves arterial travel-time, which encourages EnableATIS to redirect more travelers to use arterials. This will impact the traffic flow on arterials and thereby impact the performance of MMITSS.

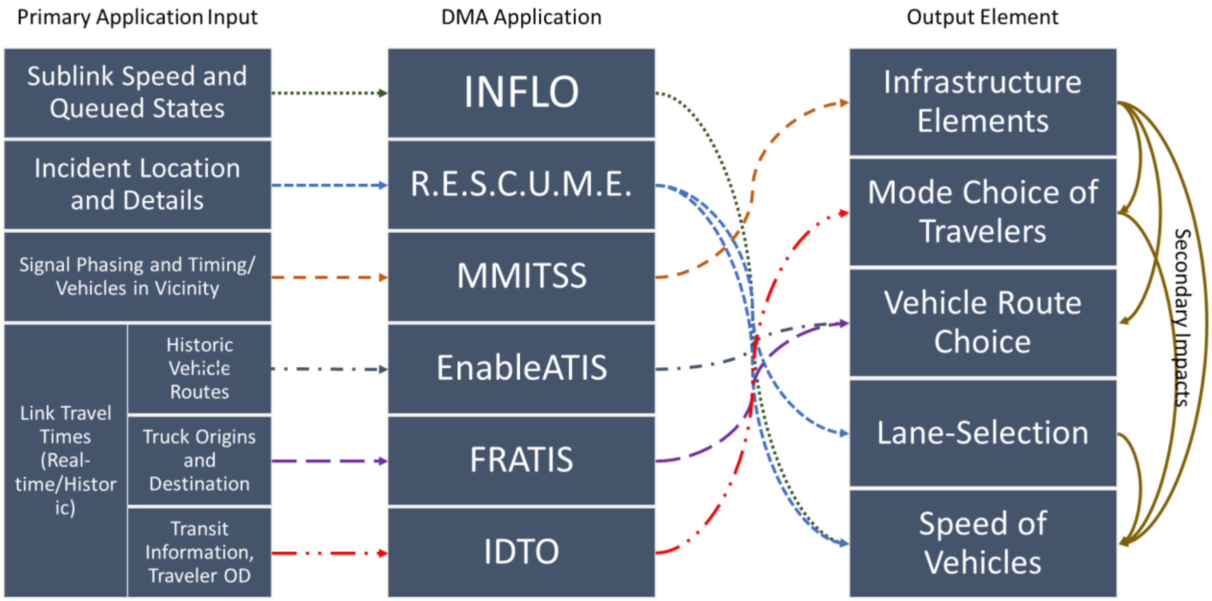


Figure 5-4: Comparison of DMA Application Inputs and Outputs on a Transportation System [Source: Booz Allen]

5.2.5 Shared Application Costs

In order to assess shared costs for DMA applications, the team evaluated the cost-model used by the DMA National Impacts Assessment team. The deployment costs for applications were originally computed based on the Cost Overview for Planning Ideas & Logical Organizational Tool (CO-PILOT) assumptions.[27] The summary of applications and the costs they share are provided in Table 5-2. Please note that the applications assessed in this model and the AMS project may vary and the CO-PILOT tool is only meant for estimating rough deployment costs. Costs have been classified into categories based on the physical element on which each cost will incur.

Table 5-2: DMA Applications that Share Costs

Dynamic Mobility Application	***INC-ZONE***	***RESP-STG***	***SPD-HARM***	***Q-WARN***	***CACC***	***FSP***	***TSP***	***PREEMPT***	***I-SIG***	***T-CONNECT***	***T-DISP***	***FRATIS***	***DR-OPT***
Transit Vehicles Operator													
Training	✓		✓	✓			✓		✓	✓	✓		
Public Safety Vehicles													
On-board Unit (OBU)	✓	✓						✓	✓				

[27] https://co-pilot.noblis.org/CVP_CET/

Dynamic Mobility Application	***INC-ZONE***	***RESP-STG***	***SPD-HARM***	***Q-WARN***	***CACC***	***FSP***	***TSP***	***PREEMPT***	***I-SIG***	***T-CONNECT***	***T-DISP***	***FRATIS***	***DR-OPT***
Software Packages	✓	✓						✓	✓				
Signalized Intersection													
Backhaul communications upgrade			✓	✓		✓	✓	✓	✓		✓		
Inductive Loop Detectors			✓	✓					✓				
Roadside Equipment (RSEs)			✓	✓		✓	✓	✓	✓		✓		
Signal controllers			✓	✓		✓	✓	✓	✓				
RSE Planning & Design			✓	✓		✓	✓	✓	✓		✓		
Pucks (Sub-surface temperature sensors)				✓					✓				
Road Weather Information System (RWIS) pavement and atmospheric sensor system				✓					✓				
Trucks													
Truck Retrofit kit / OBU	✓	✓	✓	✓	✓	✓			✓			✓	✓
Truck software package	✓	✓	✓	✓	✓	✓			✓			✓	✓
Mobile (cellular-based) carry-in device	✓		✓	✓									✓
Mobile device cellular data plan for 12 months	✓		✓	✓									✓
Drivers for Public Safety Vehicles													
Training	✓	✓						✓	✓				
Drivers for Trucks													
Driver Training Hours: Trucks	✓	✓	✓	✓	✓	✓			✓			✓	✓
Freeway Segments													
Backhaul communications upgrade			✓	✓	✓						✓	✓	
Inductive Loop Detectors			✓	✓	✓							✓	
Roadside Equipment (RSEs)	✓		✓	✓	✓						✓	✓	
RSE Planning & Design	✓		✓	✓	✓						✓	✓	
Pucks (Sub-surface temperature sensors)				✓	✓								
Road Weather Information System (RWIS) pavement and atmospheric sensor system				✓	✓								
CCTV Camera				✓	✓								
Transit Vehicles													
Transit Retrofit kit / OBU	✓		✓	✓			✓		✓		✓		
Transit software package	✓		✓	✓			✓		✓	✓	✓		

Dynamic Mobility Application	INC-ZONE	RESP-STG	SPD-HARM	Q-WARN	CACC	FSP	TSP	PREEMPT	I-SIG	T-CONNECT	T-DISP	FRATIS	DR-OPT
Mobile (cellular-based) carry-in device	✓		✓	✓						✓	✓		
Mobile device cellular data plan for 12 months	✓		✓	✓						✓	✓		

As summarized in the table, several applications share unit costs in running DMA applications. In general, applications within a bundle share largest number of elements.

5.3 Results Summary

In order to assess the impact of application combinations, MMITSS, INC-ZONE, and INFLO were assessed in isolation and in combination. It was found that these applications are synergistic in nature, with a combination of applications showing better performance measures than in isolation, but at higher market penetration of connected vehicle technology (greater than 50 percent).

INFLO and INC-ZONE are both freeway-based applications. They were assessed in isolation and in combination for shockwave reduction (INFLO-specific performance measure) and effective throughput increase (INC-ZONE-specific performance measure). At market penetrations about 10 percent, these applications performed better when combined. For example, at 50 percent market penetration, the average reduction in shockwaves increased from 13 percent to 15 percent when INFLO was combined with INC-ZONE. The average increase in the throughput of open lanes in an incident zone increased from 50 percent to 58 percent when INC-ZONE was combined with INFLO.

At higher than 10 percent market penetration, the tactical DMA applications, such as INFLO, MMITSS, and INC-ZONE, produced greater benefits in combination than in isolation. Strategic applications, such as EnableATIS, FRATIS, and IDTO, are neither synergistic nor conflicting based on our qualitative assessment. Application combinations between the two sets also do not directly influence network characteristics in a synergistic or conflicting manner.

INFLO and MMITSS applications were assessed for improvement in overall network delay in isolation and in combination. At any market penetration, the combination was shown to be better than the isolated applications. For example, at 50 percent market penetration, the reduction in overall delay in the network increased from -1 percent (INFLO only) and 3 percent (MMITSS only) to almost 11 percent when the applications were combined. Therefore, the applications are synergistic. Similar trends were also shown for the INC-ZONE and MMITSS application combination, where the reduction in average network delay increased from 2 percent to almost 5 percent. Please note that these assessments were done on specific operational conditions. An operational condition is a combination of travel demand, incident severity, and weather impacts.

The team also evaluated combinations of tactical group applications with strategic group applications, using qualitative research that looks into the specific network entity that is controlled by each application. No primary conflict or synergy was found since these groups of applications impact different aspects of the network. For example, applications such as EnableATIS, FRATIS, and IDTO impact the mode/route choice of the travelers whereas applications such as INFLO, INC-ZONE, and MMITSS impact the driver behavioral parameters, such as speed and lane selection.

Chapter 6. Operational Conditions, Modes, and Facility Types

This chapter primarily answers the research questions with respect to DMA applications and bundles under different operational conditions, modes, and facility types. The San Mateo testbed is used to present the results of INC-ZONE, INFLO, and MMITSS application/bundle results and the Phoenix testbed is used for EnableATIS, IDTO, and FRATIS applications/bundles. Both the San Mateo and Phoenix testbeds were assessed for four different operational conditions. For the evaluation of modes and facility types, some of the applications are specific to certain modes (e.g., freight vehicles, transit vehicles) and facility types (e.g., freeway, arterial).

6.1 Research Questions and Hypotheses

The following research questions are answered using this analysis:

1. What DMA bundles or combinations of bundles yield the most benefits for specific operational conditions?
2. Under what operational conditions are specific bundles the most beneficial?
3. Under what operational conditions do particular combinations of DMA bundles conflict with each other?
4. Which DMA bundle or combinations of bundles will be the most beneficial for certain modes and under what operational conditions?
5. Which DMA bundle or combinations of bundles will be most beneficial for certain facility types (e.g., freeway, transit, arterial) and under what operational conditions?
6. Which DMA bundle or combinations of bundles will have the most benefits for individual facilities versus system-wide deployment versus region-wide deployment and under what operational conditions?
7. Are the benefits or negative impacts from these bundles or combinations of bundles disproportionately distributed by facility, mode, or other sub-element of the network under specific operational conditions?

The given research questions try to answer a plethora of topics related to operational conditions, modes, and facility types. The tactical applications/bundles, such as INFLO, INC-ZONE, and MMITSS, are specific to a facility type and the strategic applications/bundles, such as EnableATIS, IDTO, and FRATIS, are specific to certain modes.

In order to answer these questions, the following hypotheses were made:

1. Certain DMA bundles or combinations of bundles will yield the highest benefits under specific operational conditions. This will depend on specific operational conditions that are targeted by individual applications.
2. A DMA bundle will yield the highest benefits only under certain operational conditions. For example, on non-incident days, INC-ZONE will have a limited impact.

3. Certain combinations of bundles will conflict with each other under specific operational conditions, resulting in no benefits or reduced benefits.
4. Certain DMA bundles or combinations of bundles will yield the highest benefits for specific modes and under certain operational conditions.
5. Certain DMA bundles or combinations of bundles will yield the highest benefits for specific facility types and under certain operational conditions.
6. Certain synergistic DMA bundles will yield the most benefits when deployed together on individual facilities rather than as system-wide or region-wide deployments and under certain operational conditions and vice versa.
7. Benefits or negative impacts from bundles will be unevenly distributed by facility, mode, or other sub-element of the network.

6.2 Analysis Approach and Research Findings

San Mateo and Phoenix testbeds are used in application assessments under different operational conditions. A mapping of the applications versus the testbed it was assessed with is given in Section 3.1. In Table 6-1, the six applications/bundles are mapped to their applicable modes and facility types. The specific operational conditions that are used for the two testbeds are provided in Table 6-2.

Table 6-1: Mapping Applications to Modes and Facility Types

Application/Bundle	*Applied Modes*	*Applied Facility Types*
EnableATIS	All Modes	All Facility Types
FRATIS	Freight Vehicles	All Facility Types
IDTO	Transit Vehicles	All Facility Types
INFLO	All Modes	Freeways
INC-ZONE	All Modes	Freeways
MMITSS	All Modes	Signalized Arterials

Table 6-2: Operational Conditions for San Mateo and Phoenix

San Mateo	*Phoenix*
Medium Demand/High Incident (MD-HI)	High Demand/Low Incident (HD-LI)
Medium Demand/High Incident/Wet Weather (MD-HI-WW)	High Demand/High Incident (HD-HI)
Medium Demand/No Incident (MD-NI)	Low Demand/Low Incident (LD-LI)
High Demand/Low Incident (HD-LI)	High Demand/Medium Incident/Wet Weather (HD-MI-WW)

The next subsections expand on the evaluation of specific applications and application combinations under different operational conditions.

6.2.1 INC-ZONE Assessment

INC-ZONE was assessed under different operational conditions for five different levels of market penetration, 10 percent, 25 percent, 50 percent, 75 percent, and 95 percent. Please note that the INC-ZONE application is localized to the incident area and is different for different operational conditions. Section 3.2 provides details on the simulated incidents. The two performance measures assessed were reduction in incident zone speed, which is the average travel speed of the open lanes, and the effective increase in incident zone throughput in terms of the number of vehicles per lane per hour during the incident. As shown in Figure 6-1, the performance increases as market penetration increases with most of the benefits achieved by 50 percent market penetration.

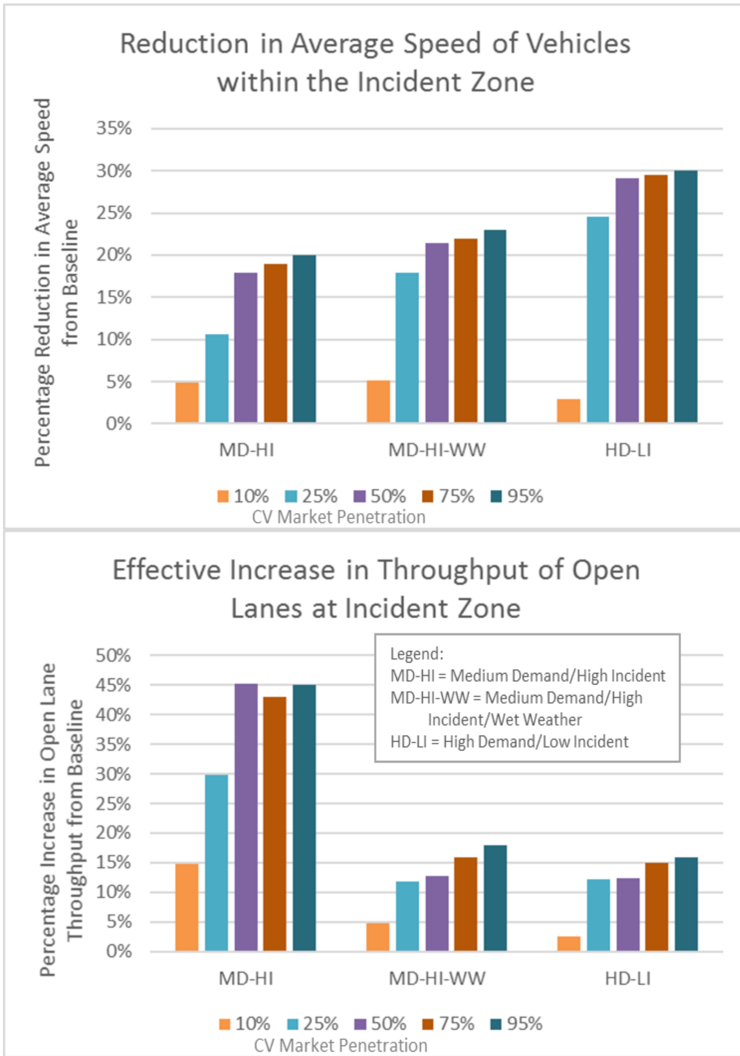


Figure 6-1: Performance of INC-ZONE under Different Operational Conditions [Source: Booz Allen]

As far as reduction in average speed of vehicles are concerned, the high-demand operational condition showed maximum percentage benefits with an average reduction of up to 30 percent (57.2 mph to 40.0 mph) at 95 percent market penetration. The performance under medium demand was similar under dry and wet weather conditions. The maximum savings under 95 percent is 20 percent for dry (69.5 mph to 55.6 mph) and 23 percent for wet (57.4 mph to 44.2 mph). When the performance in terms of increase in throughput of open lanes is concerned, the maximum savings were shown by medium demand-high incident operational condition than the other two operational conditions. The highest increase in throughput was nearly 45 percent. Open-lane throughput is defined here as the number of vehicles that the open lanes served in a given period of time (incident duration). For MD-HI cluster, the section throughput had a great increase compared to other clusters. This was because the baseline throughput was very low due to three of the five “left” lanes being closed, and INC-ZONE was able to streamline the flow early on to reduce the impact of bottleneck. The throughputs of incident zones are provided in Table 6-3. Please note that Incident 3 blocked all the lanes on the freeway and therefore INC-ZONE application was not useful in streamlining the throughput.

Table 6-3: Open Lane Throughput Under Different Market Penetrations and Operational Conditions

Incident ID	***Operational Condition***	***Lanes Blocked***	***Incident Duration***	***Throughput Under Different Market Penetrations of INC-ZONE (veh/hr summed for all open lanes)***					
				Baseline	10%	25%	50%	75%	95%
1	MD-HI	3 left lanes	33 minutes	1442	1654	1872	2093	2062	2091
2	MD-HI-WW	1 left lane	28 minutes	4136	4268	4512	4555	4674	4756
3	MD-HI-WW	All lanes	6 minutes						
4	MD-HI-WW	2 right lanes	34 minutes	2691	2855	3073	3097	3202	3256
5	HD-LI	2 left lanes	27 minutes	1598	1638	1792	1795	1838	1854

Interestingly, it was found that the most favorable operational condition for INC-ZONE is dependent on the performance measure considered. There is more of a reduction in incident zone speed under higher demand and the increase in effective throughput is greater under medium demand and with dry weather conditions. This is because, under high demand, the throughput is closer to saturation, which is preventing any further improvement. Medium demand provides the best demand level for improvement in throughput when INC-ZONE is implemented. The team also performed statistical significance tests on all these experiments using a t-test and found that almost all the results are statistically significant with a 95% confidence interval. The details of this test is provided in Section 6.2.11. Only the results for 10 percent market penetration with average speed reduction has shown lesser confidence levels.

6.2.2 INFLO Assessment

The INFLO assessment was conducted using four operational conditions on the San Mateo testbed and used US-101 northbound as the primary harmonized corridor. Simulations were performed using 2:30 pm to 7:30 pm calibrated networks; however, INFLO was only applied within the interval of 3:30 pm to 6:30 pm, assuming the time required for congestion to build up. The INFLO application specifications were similar to the Impact Assessment work, with 0.5 mile spaced detector reporting and 0.1-mile geographic resolution of the application. INFLO’s speed harmonization was performed at 5 miles per hour increments from 30 to 65 miles per hour. Specific details on how the application was modeled are given in Appendix C.

Figure 6-2 shows a comparison of INFLO-specific performance measures for 10 percent, 25 percent, 50 percent, 75 percent, and 95 percent market penetration when compared to the "baseline" scenario for different operational conditions. The two performance measures assessed were reduction in shockwaves on the freeway and reduction in speed variations. Reduction in shockwaves represents speed harmonization between adjacent sublinks and reduction in speed variations represent harmonized movement within a sublink. As shown in Figure 6-2, most performance of the applications is achieved as the market penetration reaches 50 percent. The reduction in shockwaves is the highest for the MD-NI operational condition that represents dry weather, medium demand, and no incidents. The benefits ranged between 17 percent and 25 percent for different rates of market penetration. Similarly, the lowest benefits are shown by the medium demand and high incident operational condition with benefits ranging from 6 percent to 14 percent. Similarly, the reduction in speed variation was also highest under MD-NI operational conditions, with reductions ranging from 20 percent to 29 percent. Statistical significance test shows very high significance of these results (Section 6.2.11), with the exception of the HD-LI operational condition with 10 percent market penetration for shockwave reduction. A confidence interval of 95 percent is used in these tests.

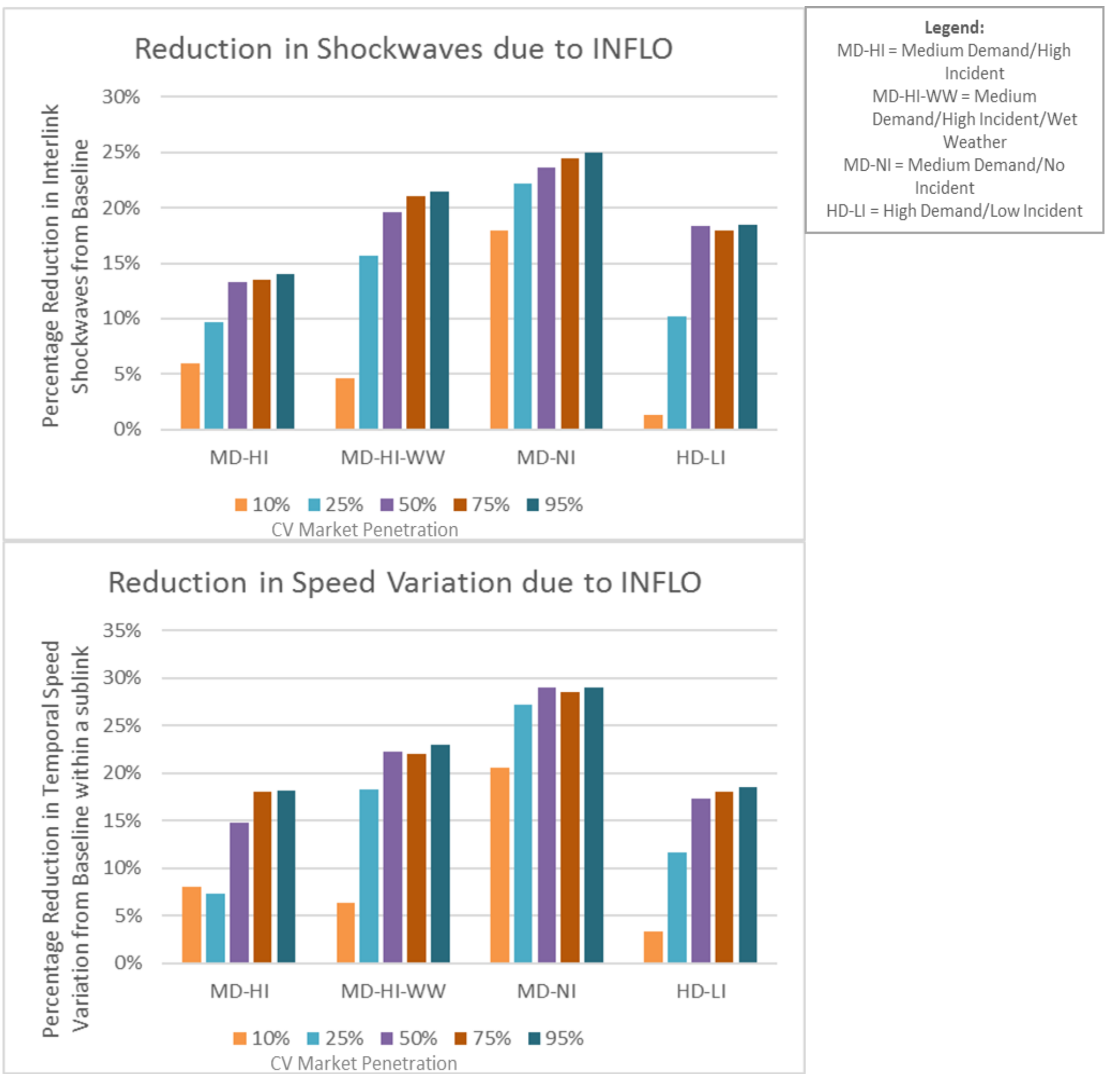


Figure 6-2: Performance of INFLO under Different Operational Conditions [Source: Booz Allen]

6.2.3 MMITSS Assessment

The MMITSS application bundle, specifically the I-SIG application, was assessed at various levels of market penetration (10 percent, 25 percent, 50 percent, 75 percent, and 95 percent) under the four operational conditions for the San Mateo testbed. The two performance measures assessed are reduction in the arterial travel time as well as the reduction in maximum queue lengths on side streets. I-SIG was used for the evaluation and aims at optimizing the signal phases along the signalized arterial for minimizing the travel time. Full details on how it is modeled in the San Mateo testbed are provided in Appendix E. The results are shown in Figure 6-3.

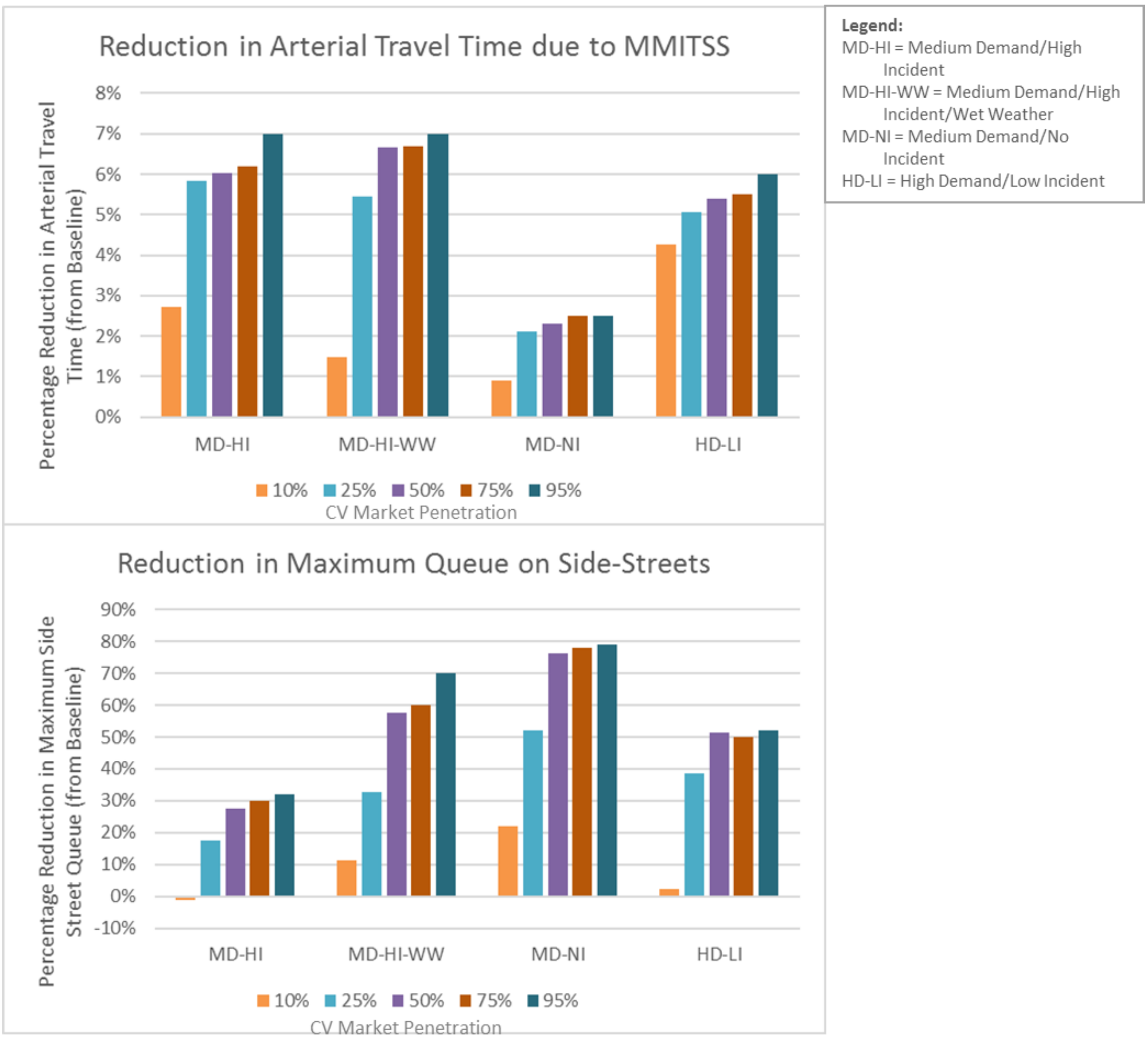


Figure 6-3: MMITSS Performance under Different Operational Conditions [Source: Booz Allen]

As shown in Figure 6-3, the improvement in arterial travel time due to MMITSS increases with increase in CV market penetration in all the operational conditions assessed. For example, under medium demand, high incident operational condition, the reduction in arterial travel time increases from 2.8 percent at 10 percent market penetration to 7 percent under 95 percent market penetration. Medium demand and high incident operational conditions (dry and wet weather) is also the most favorable operational condition for this performance measure. It was seen that under high incident severity that is primarily focused on the freeways, vehicle volumes from the ramps to the arterial is causing increased side-street queues at the MMITSS-controlled intersections. Therefore, the reduction in maximum side-street queue is lesser than other operational conditions. As far as the reduction in maximum queue is concerned, the results are a bit different. The I-SIG application provides significant reduction in the queue built-up on side streets by recommending phase transitions as it gets advanced calls from connected vehicles. The application showed up to 80 percent reduction in arterial side-street queues under MD-NI (medium demand/no incident) conditions at 95 percent market penetration. This is the most favorable operational condition because even 10 percent market penetration is able to reduce the maximum queue by over 20 percent.

The team also performed statistical significance tests on these results based on 5 random-seed runs for each of the scenario. The results are tabulated in Section 6.2.11. The t-test with 95-percent confidence interval showed most of the results to be statistically significant. The only exceptions were some of the cases with 10 percent market penetration where the noise introduced by the randomized experiments were higher than the benefits achieved.

6.2.4 EnableATIS Assessment

EnableATIS implemented in the Phoenix testbed aims to use link-specific travel-time information to guide travelers through uncongested routes and hence save travel time. Unlike other applications, the market penetration of EnableATIS is composed of two components – pre-trip information and en-route information. The travelers with pre-trip information uses the link travel times at the start of their trip to compute an optimum route for their travel, whereas the travelers with en-route information continuously monitor the travel-time changes and dynamically switch routes. The team also evaluated the effectiveness of EnableATIS in comparison to VMS.

1. Do nothing case where no system is providing traveler information.
2. Case where VMS are used to distribute traveler information across the network. VMS are utilized at locations upstream of the bottleneck locations under different operational conditions. These locations are shown in Figure 6-4.
3. Case where VMS messages are supplemented with 20 percent of travelers receiving pre-trip route information.
4. Case where 50 percent of the travelers receiving pre-trip route information. This case was used as baseline as shown in Figure 6-6.
5. Case where 50 percent of the travelers choose their routes prior to their departure based on current traveler information and 20 percent of the travelers make en-route decisions based on real-time information using connected vehicle technology.
6. Case where 50 percent of the travelers receive pre-trip information and 30 percent receive en-route information using CV technology to make their real-time routing decisions.
7. Case where 80 percent of the travelers receive pre-trip information and 30 percent receive en-route information using CV technology to make their real-time routing decisions.

A system-wide analysis was conducted with EnableATIS and the results are shown in Figure 6-5. As shown in the figure, VMS systems may increase the system-wide travel time even though it can relieve the severity of congestions at bottlenecks. This is because VMS can only reroute vehicles to other routes without considering the system-wide impact and those rerouted vehicles may create additional congestion at other locations. In contrast, EnableATIS will reallocate vehicles' routes systematically and not only relieve the congestions at bottlenecks but also throughout the whole system. However, the average travel distance shows that EnableATIS may considerably increase the travel distance because of its systematic rerouting policy.

Figure 6-5 shows the absolute average travel time experienced by vehicles when the EnableATIS system is used by travelers. As shown, there is a significant reduction in travel time as the market penetration of pre-trip and en-route EnableATIS increase. However, the travel time actually increases when the pre-trip market penetration increases without increase in en-route penetration. This is shown from the fact that the average travel time for the scenario with 80 percent pre-trip and 30 percent en-route EnableATIS is worse than that for the scenario with 50 percent pre-trip and 30 percent en-route. This is because more passengers are switching routes based on the traffic conditions prior to the trip and without any en-route information, these vehicles are congesting the typical alternate routes. For example, an incident on a freeway will direct the travelers to use a parallel arterial. But the number of travelers who can effectively detour and maintain their travel time is significantly less. Therefore, en-route information is vital in suggesting dynamic detours to travelers that can help in reducing delays.

In order to assess the operational conditions under which EnableATIS performs well, percentage savings in travel time was derived from these results and are shown in Figure 6-6. As shown, there is up to 40 percent reduction in travel time when the EnableATIS system is used at the right pre-trip/en-route market penetration. Please note that in real-life, the baseline condition will have some travelers using pre-trip information to adjust their routes. The actual savings in travel time may not be up to 40 percent, since the freeway-arterial calibration data was not well-balanced, since they were coming from two different sources. This effectively displaced several vehicles to the arterials (whose demand was underrepresented), when EnableATIS was activated.

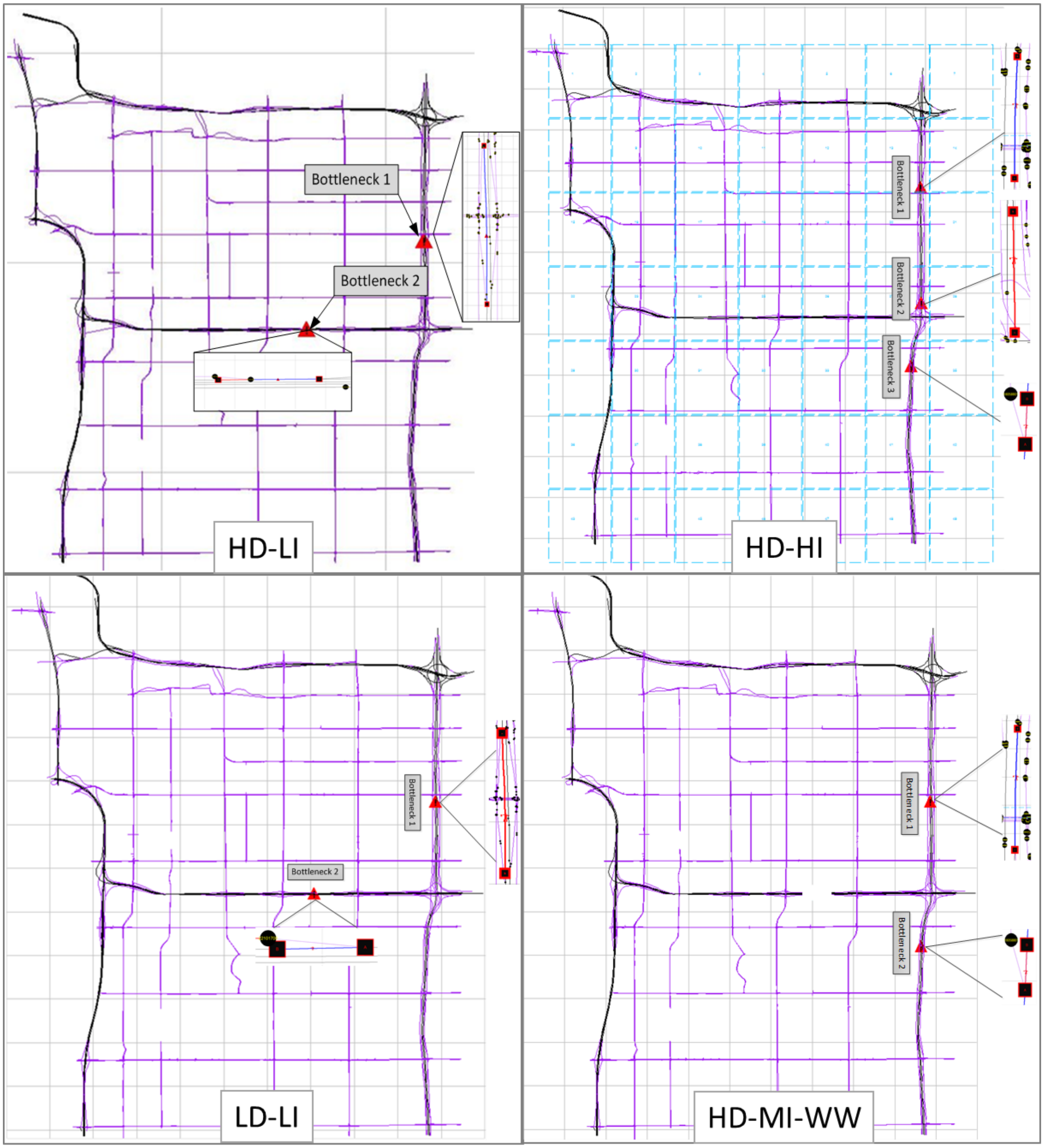


Figure 6-4: Bottleneck Locations for Phoenix Testbed under Different Operational Conditions [Source: ASU]

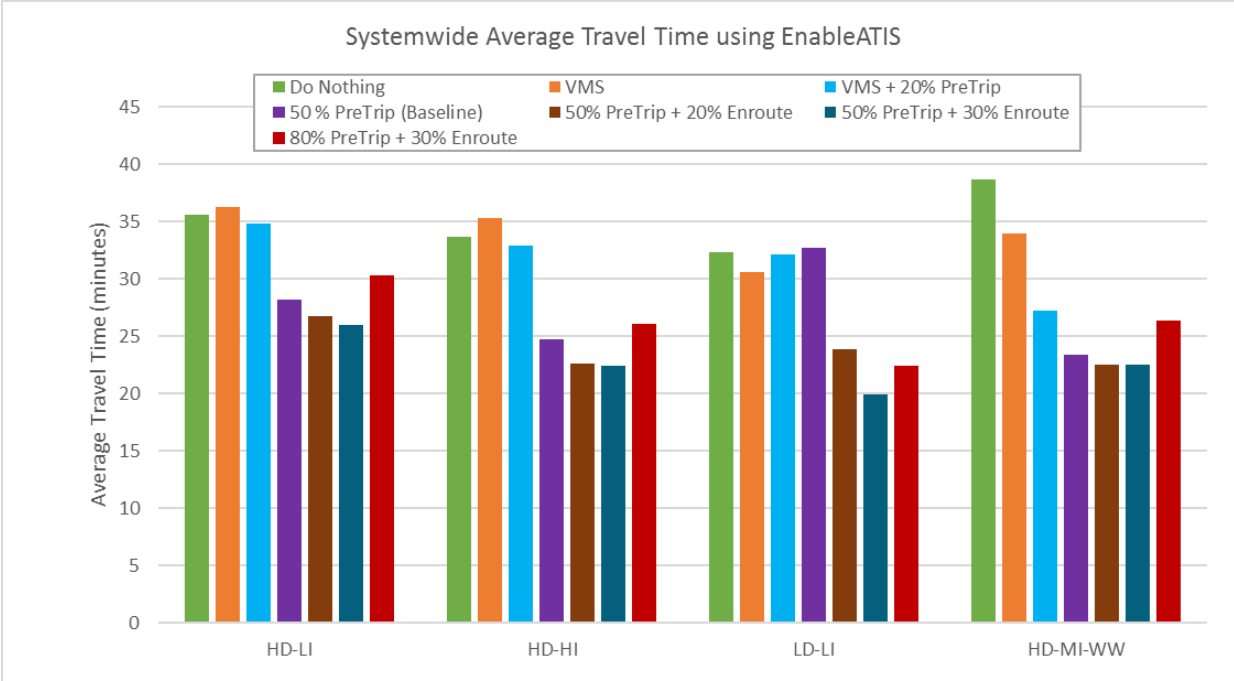


Figure 6-5: Performance of EnableATIS under Different Operational Conditions [Source: ASU]

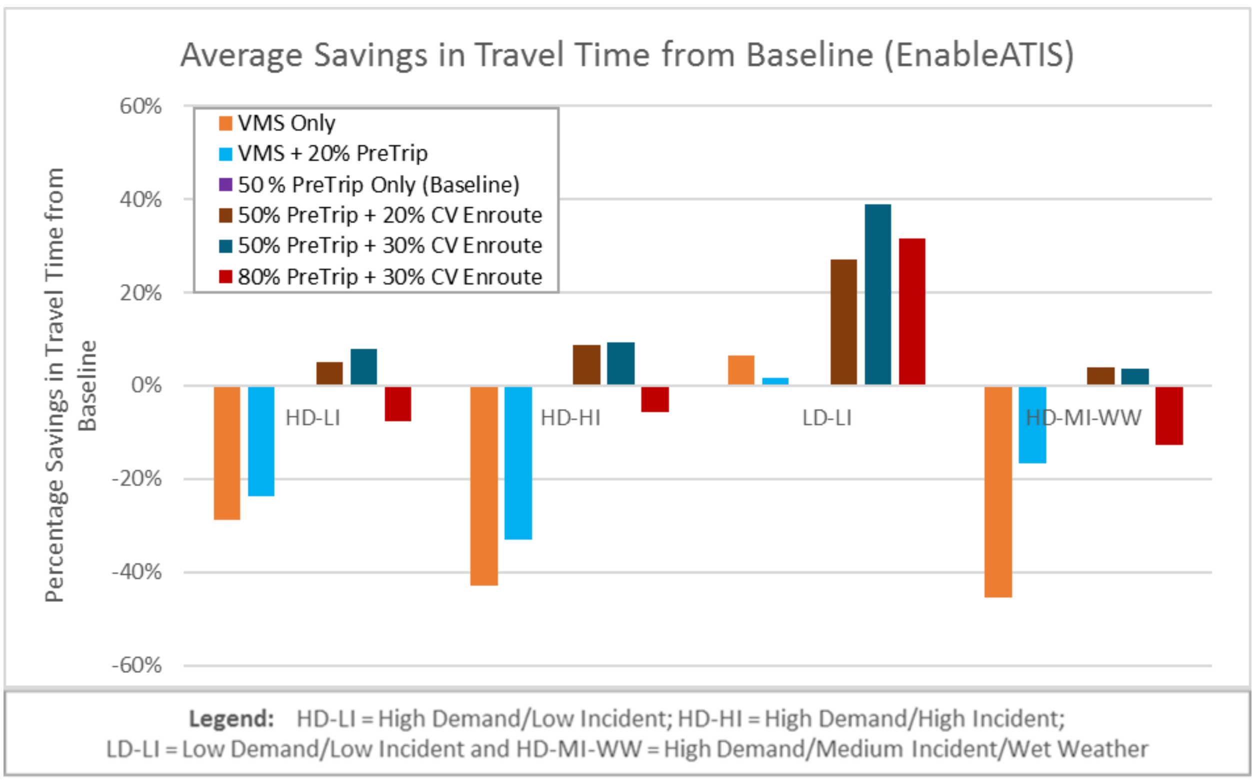


Figure 6-6: Savings in Travel Time Due to EnableATIS [Source: ASU]

6.2.5 FRATIS Assessment

FRATIS application aims at reducing truck travel time by providing real-time route guidance to the trucks using available link travel time information. This is different from the routing problems used in EnableATIS since trucks have multiple destinations. The Phoenix testbed evaluated FRATIS application, which was developed based on the characteristics of Freight-specific Planning and Performance application. The application considers multi-destination trucks and uses real-time traffic conditions and prediction to determine optimum order of delivery and routes. The prototype application could not be used in the context of simulation due to technical complexity of the application and the simulation-based testbeds.

The Phoenix testbed team developed a version of the application that replicates some of the functionalities of the actual FRATIS application. More details on how the application was developed and what functionalities were used are provided in the Appendix G. The AMS-version of the application assumes intra-city trucks with an origin and multiple destinations and optimizes the routes and order of delivery destinations based on real-time traffic (link-specific travel times) from the DTALite model. For this limited evaluation, we assumed three trucks with different origins and lists of destinations as shown in Figure 6-7. Mathematically, the route guidance problem for trucks can be viewed as a special version of the vehicle routing problems. In particular, during a truck trip, the truck needs to decide a proper sequence to visit those locations. Solving Vehicle Routing Problems (VRP) is typically very difficult when problems become large-scale and therefore a fast heuristic algorithm based on finding the minimum total cost for all possible visiting sequences is developed in FRATIS to provide guidance for trucks. The origin and destination, departure and arriving time window from origin and for each destination for each truck, the sketched road network with link travel time information and evaluation benchmark such as total travel time should be given to the algorithm as an input. The application’s performance was assessed as the average savings in travel time of these three trucks with three delivery locations. The application assessed link travel times and optimized the delivery patterns and truck routes and thereby minimizing their travel times. This FRATIS scenario was evaluated on all the four operational conditions as shown in Figure 6-8. As shown, the average savings for each operational condition ranges from 15 percent to 47 percent with the highest improvement being for High Demand/High Incident operational condition.

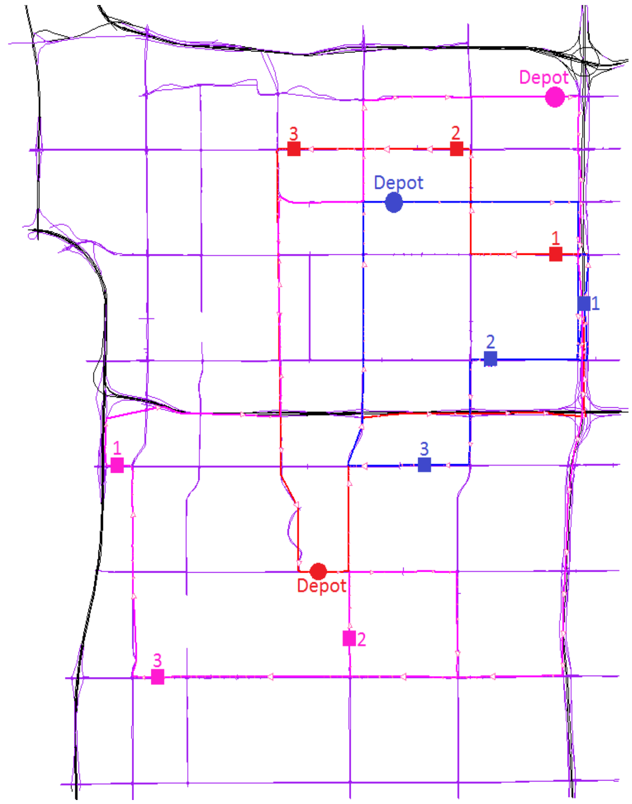


Figure 6-7: Locations of Depots and Delivery Stations for Three Trucks (Red, Blue, and Pink) [Source: ASU]

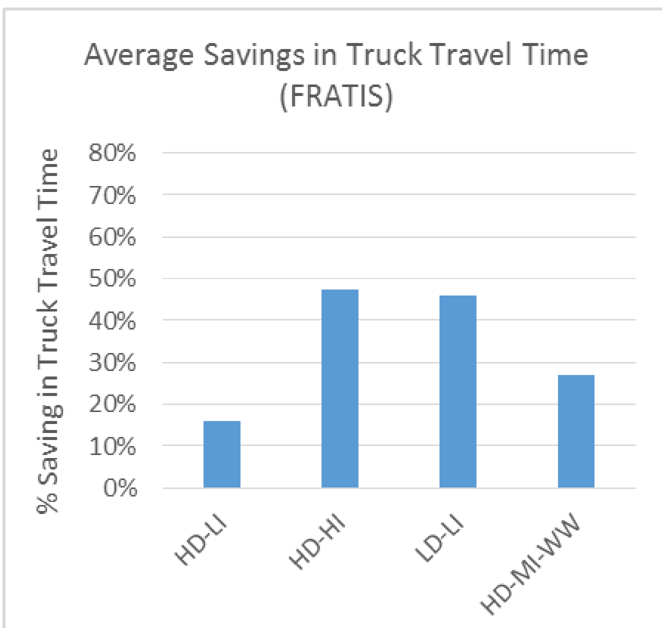


Figure 6-8: Average Travel Time Savings for Trucks Using FRATIS Application [Source: Booz Allen]

6.2.6 IDTO Assessment

Two applications within the IDTO bundle are evaluated in the Phoenix testbed – T-DISP and D-RIDE. Both these algorithms were developed to reflect their design purpose for simulation within the DTALite framework. Details on their modeling aspects are described in the Appendix H of this report. For assessing the effect of operational conditions, only T-DISP application has been evaluated. T-DISP application aims at finding the optimized transit path for transit travelers from their origin to their destination. Compared to the standard shortest path finding algorithms, the uniqueness of transit path finding algorithm is that the algorithm needs not only to determine a non-stop transit path for passengers but also consider possible transferring (i.e., waiting) from one line to another line at some transit stops under defined constraints to avoid congestions and to improve travel time reliability.

The Phoenix testbed team evaluated the application under three different levels of market penetrations for the four operational conditions. The results are shown in Figure 6-9. The figure shows the average reduction in transit travel time when there is 20 percent, 50 percent, and 80 percent transit travelers using T-DISP. The figure also shows the average baseline travel time for transit passengers under different operational conditions. Please note that the average is computed by considering three types of transit passengers based on the distance between their origin and destination. Details on this computation are given in the Appendix H.

As shown in Figure 6-9, there is minimal savings in transit travel time when the market penetration is less (20 percent). However, as market penetration goes beyond 50 percent, there is considerable improvement in transit travel time. For example, at 80 percent market penetration, the average travel time improvement shown by transit travelers ranged from 6.8 percent to 11.3 percent. Data from simulation showed that medium OD travelers had the highest benefits ranging between 15 percent and 27 percent, whereas the travelers with short OD showed marginal 1 percent reduction in travel time. The travelers with long OD have showed less than average reduction in travel time. This is likely because the evaluation was done with maximum transfers being capped at a realistic value of two.

D-RIDE Evaluation was conducted using a limited prototype that was developed by the Phoenix testbed team and used agent-based modeling. Details on the model are provided in the Appendix H. For the evaluation, the team considered up to 100 agents (50 vehicles + 50 passengers) at the same time using reasonable and realistic assumptions. The initial locations of vehicles and passengers are randomly placed on the transportation network of City of Tempe including thousands of nodes and links. Without loss of generality, the vehicle capacities are uniformly set as two passengers. Passengers have various OD pairs and departure/arrival time windows and 50 vehicles available at different locations. D-RIDE was able to minimize the number of required vehicles, but in some cases, failed to serve some passengers.

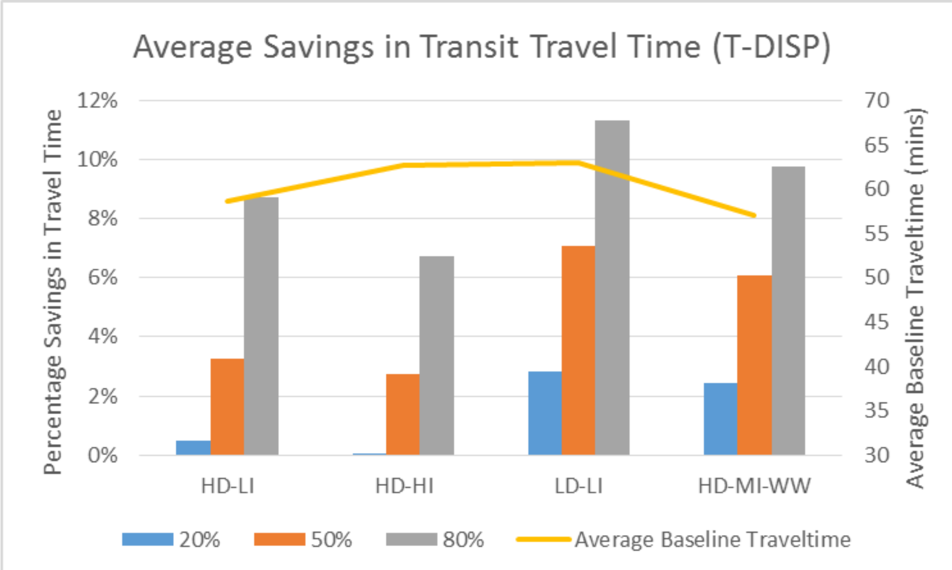


Figure 6-9: Average Transit Travel Time Savings Due to T-DISP under Different Operational Conditions [Source: ASU]

Table 6-4 shows the performance of D-RIDE application in serving passengers with reduced number of vehicles. After optimization and simulation, it is found that the average travel time was 33 minutes and the average speed was 31 mph for the vehicles. All passengers were picked up and delivered within their time windows. The computing time was acceptable as well. Please note that D-RIDE was prototyped as a proof-of-concept application based on the original D-RIDE's vision. Hence only a limited test with 100 agents were performed.

Table 6-4: Performance of D-RIDE

Test case number	*Number of iterations*	*Number of passengers*	*Number of vehicles*	*Number of passengers not served*
1	6	4	2	0
2	6	10	5	1
3	6	20	6	0
4	6	40	12	0
5	6	50	15	0

6.2.7 INFLO + INC-ZONE Combination

In addition to assessing INC-ZONE and INFLO in isolation, the team also conducted simulations to evaluate the impact of INFLO and INC-ZONE in combination under different operational conditions using the San Mateo testbed. Connected vehicle market penetration of 50 percent was used in this assessment so that the performance of the applications under a mixed connected vehicle environment can be assessed. Please note that only three out of four operational conditions were used in this evaluation, since the MD-NI (Medium Demand/No Incident) operational condition did not have an incident. The simulation details are similar to what was used in Sections 6.2.1 and 6.2.2 with INFLO harmonizing speeds across US-101 NB freeway and INC-ZONE application acting localized to the incident area for the temporal duration of the incident. Two performance measures were assessed to represent both INFLO and INC-ZONE performance and the results are shown in Figure 6-10. They are average reduction in shockwaves and average reduction in vehicle speed at the incident zone.

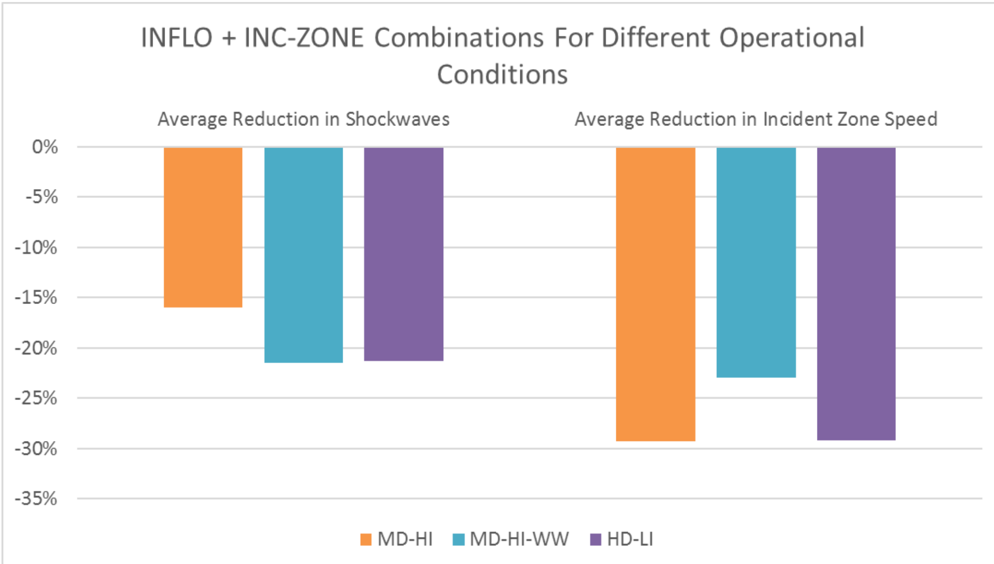


Figure 6-10: Performance of Combination of INC-ZONE and INFLO under Different Operational Conditions [Source: Booz Allen]

As shown in Figure 6-10, INFLO and INC-ZONE performed differently as far as the performance measures for either application are concerned. For example, the best average reduction in shockwaves were demonstrated under MD-HI-WW and HD-LI operational conditions at about 21 percent, whereas the best average reduction in incident zone speed were demonstrated under MD-HI and HD-LI operational condition at about 29 percent. Conclusively, the most beneficial operational condition for INFLO+INC-ZONE combination is the HD-LI operational condition. This difference in performance under different operational conditions is likely as a consequent to the interaction between the speed advisories given by INFLO and INC-ZONE. However, as shown in Section 5.2, these applications are beneficial in combination.

6.2.8 MMITSS and INC-ZONE Combination

Similarly, the team assessed the MMITSS and INC-ZONE combination under the different operational conditions using the San Mateo testbed. The MMITSS application was enabled at the north most eight signal controllers on the El Camino Real arterial and the INC-ZONE was used in conjunction with incidents on the US-101 freeway. Since MMITSS and INC-ZONE application worked at different geographic regions of the network and facility types, overall performance measures were used to assess them, namely average delay and average speed. These mobility-based measures denote the performance of all vehicles in the network throughout the simulation (even though application's performance interval need not be for the entire simulation). The results are shown in Figure 6-11.

As shown in Figure 6-11, MMITSS and INC-ZONE together improves overall mobility in the network. The average delay of vehicles on the network reduces by 6 to 8 percent, whereas the average speed of vehicles on the network increases by 5 to 7 percent. Among the three operational conditions assessed (Medium Demand/No Incident operational condition was not assessed for this combination since INC-ZONE works only when there are incidents in the network), medium demand with high incident severity was deemed to be the most favorable operational condition for this application combination. This is likely because in the absence of wet weather and high demand, the transportation network has room for improvement when MMITSS streamlines the vehicle flow along the arterial and the INC-ZONE enhances the throughput of open lanes during an incident.

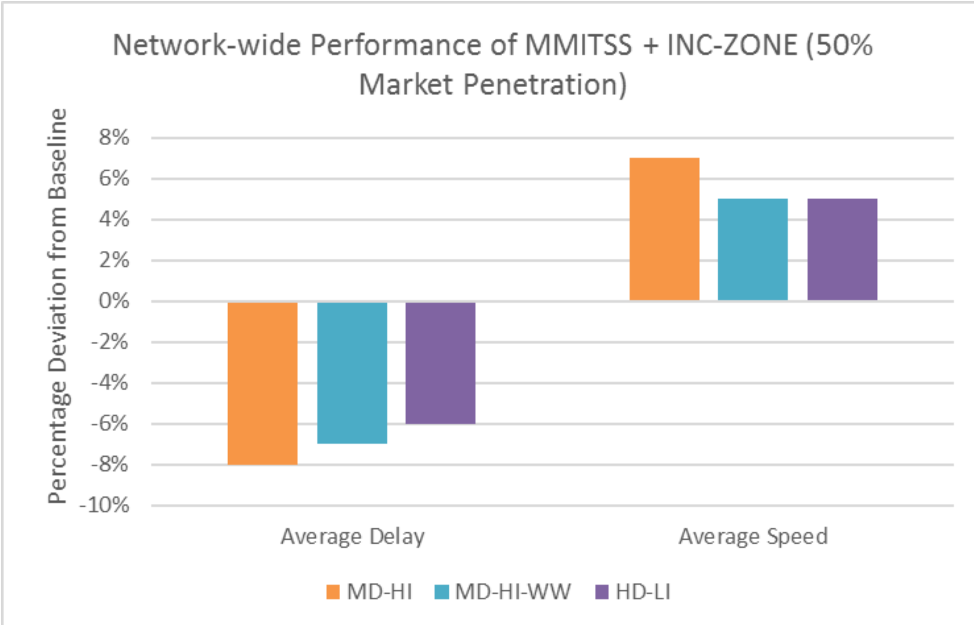


Figure 6-11: Performance of Combination of MMITSS and INC-ZONE under Different Operational Conditions [Source: Booz Allen]

6.2.9 MMITSS and INFLO Combination

MMITSS and INFLO combination was also assessed for the four different operational conditions using San Mateo network. I-SIG application of the MMITSS bundle was used to enhance mobility of the arterial by reducing corridor travel time and the queue build-up on side streets and INFLO was used to reduce shockwaves and harmonize speeds along the parallel freeway. Since INFLO and MMITSS works on different facility types and geographic regions of the network, overall performance measures of average delay and average speed was used to compare different operational conditions. The improvement of mobility in terms of these performance measures are shown in Figure 6-12.

As shown in the figure, the percentage reduction in average delay of vehicles in the network ranges from 7 to 12 percent from the baseline scenario and the percentage increase in average speed of vehicles ranged from 1 to 3 percent. Both performance measures showed maximum benefits for the medium demand and high incident severity operational condition, whereas least benefits are given when the demand is high or when there is wet weather. This is likely because in the absence of wet weather and high demand, the transportation network has room for improvement when MMITSS streamlines the vehicle flow along the arterial and the INFLO harmonizes the vehicle movement across the freeway.

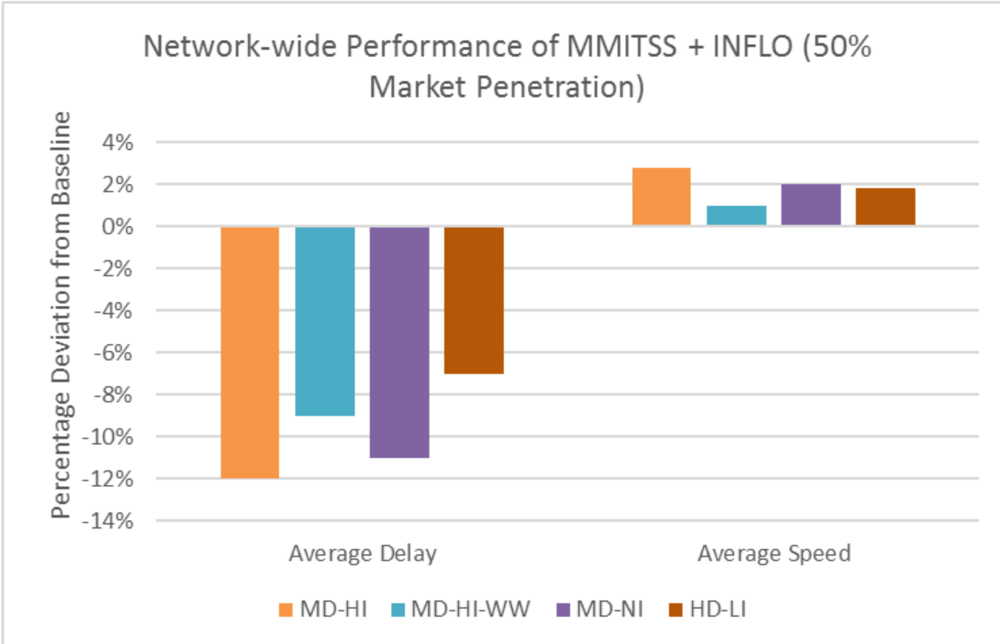


Figure 6-12: Performance of Combination of MMITSS and INFLO under Different Operational Conditions [Source: Booz Allen]

6.2.10 Other Combinations

The team did not assess combinations within the strategic bundles of applications, namely – EnableATIS, FRATIS, and IDTO since these applications apply to different road user types. EnableATIS aims at minimizing delay across the network by dynamically assigning routes to vehicles based on real-time link travel times. FRATIS applies similar logic, but only to trucks and IDTO helps transit travelers in finding matching connections and reduce their net transit travel time.

6.2.11 Statistical Significance

The team conducted statistical significance test for some of the scenarios to assess their significance of the results stated in this report. An unpaired t-test is performed to compare the contributions from the application and in each case, the comparison was conducted with respect to the baseline performance measure. Table 6-5 through Table 6-7 shows the statistical significance testing performed for INC-ZONE, INFLO and MMITSS application performance measures. In all the cases, we performed 5 random-seed simulation runs for the baseline and different test cases and given the differences in simulation under different random seeds, an unpaired test was used.

The tables below show a summary of P-value calculations along with some intermediate statistics such as pooled standard deviation and t-statistic. The system performance noise added by the random seeds was assumed to be two-tailed normal distribution and a confidence interval of 95 percent was used. Therefore, the critical value of t-statistic was computed to be 2.3. Each case of statistical significance test (each row in the table) represents an experiment based on one operational condition, one performance measure, one value of Connected Vehicle market penetration and a comparison between without treatment and with treatment groups (with application and without application).

Table 6-5 shows the experiments for INC-ZONE application under three operational conditions and five different market penetrations. In all, but three cases, the INC-ZONE showed a statistically significant impact on the system performance, in terms of its ability to reduce average speed of vehicles in the incident zone and improving the throughput of open lanes. Table 6-6 shows the statistical significance analysis of INFLO application under four operational conditions and five different market penetrations. In all of the cases (except one), the INFLO showed a statistically significant impact on shockwaves and speed variations in the system. Under the HD-LI and 10 percent market penetration case, the reduction in shockwaves were only 75 percent confident in statistical significance. Table 6-7 shows the statistical significance of MMITSS application on reduction in arterial travel time and maximum side-street queues. As shown, of the 40 experiments performed, only 4 were less than 95 percent confident in statistical significance.

Table 6-5: Statistical Significance Test for INC-ZONE Application

Operational Condition	Performance Measure	Market Penet-ration	Sample Size	Mean (Baseline)	Std. Dev. (Baseline)	Mean (Test)	Std. Dev. (Test)	Pooled Std. Deviation	Computed t-Statistic	P-Value	Statistical Significance
MD-HI	Average Speed in Incident Zone	10%	5	69.25	2.45	65.85	2.61	1.6016	2.1229	0.066522	No
		25%	5	69.25	2.45	61.89	2.27	1.4922	4.9337	0.001144	Yes
		50%	5	69.25	2.45	56.89	1.78	1.3548	9.1228	1.68E-05	Yes
		75%	5	69.25	2.45	56.09	1.73	1.3403	9.8171	9.74E-06	Yes
		95%	5	69.25	2.45	55.40	1.96	1.4018	9.8805	9.28E-06	Yes
	Throughput of Open Lanes	10%	5	1862.31	24.22	1588.05	21.65	14.5293	18.8766	6.41E-08	Yes
		25%	5	1862.31	24.22	1306.48	25.75	15.8083	35.1603	4.69E-10	Yes
		50%	5	1862.31	24.22	1021.57	22.80	14.8761	56.5159	1.07E-11	Yes
		75%	5	1862.31	24.22	1061.52	23.26	15.0176	53.3238	1.7E-11	Yes
		95%	5	1862.31	24.22	1024.27	21.55	14.4992	57.7988	8.92E-12	Yes
MD-HI-WW	Average Speed in Incident Zone	10%	5	57.48	2.29	54.56	2.80	1.6166	1.8062	0.108513	No
		25%	5	57.48	2.29	47.17	2.87	1.6427	6.2754	0.000239	Yes
		50%	5	57.48	2.29	45.20	1.38	1.1945	10.2794	6.91E-06	Yes
		75%	5	57.48	2.29	44.83	1.95	1.3463	9.3931	1.35E-05	Yes
		95%	5	57.48	2.29	44.26	2.62	1.5552	8.5009	2.81E-05	Yes
	Throughput of Open Lanes	10%	5	2650.22	31.12	2524.69	20.91	16.7669	7.4869	7.01E-05	Yes
		25%	5	2650.22	31.12	2338.10	23.91	17.5502	17.7842	1.02E-07	Yes
		50%	5	2650.22	31.12	2314.30	23.73	17.5015	19.1937	5.63E-08	Yes
		75%	5	2650.22	31.12	2226.18	22.09	17.0665	24.8460	7.36E-09	Yes
		95%	5	2650.22	31.12	2173.18	22.28	17.1169	27.8695	2.97E-09	Yes
HD-LI	Average Speed in Incident Zone	10%	5	56.21	2.31	54.54	2.64	1.5678	1.0652	0.317879	No
		25%	5	56.21	2.31	42.42	1.79	1.3072	10.5463	5.7E-06	Yes
		50%	5	56.21	2.31	39.85	1.24	1.1719	13.9598	6.72E-07	Yes
		75%	5	56.21	2.31	39.63	2.53	1.5334	10.8135	4.72E-06	Yes
		95%	5	56.21	2.31	39.35	1.10	1.1438	14.7426	4.41E-07	Yes
	Throughput of Open Lanes	10%	5	2704.66	39.95	2636.47	22.10	20.4181	3.3394	0.01024	Yes
		25%	5	2704.66	39.95	2376.25	23.11	20.6410	15.9105	2.44E-07	Yes
		50%	5	2704.66	39.95	2371.74	27.80	21.7660	15.2954	3.31E-07	Yes
		75%	5	2704.66	39.95	2298.96	25.09	21.0967	19.2304	5.54E-08	Yes
		95%	5	2704.66	39.95	2271.91	23.95	20.8301	20.7750	3.02E-08	Yes

Table 6-6: Statistical Significance Test for INFLO Application

Operational Condition	Performance Measure	Market Penet-ration	Sample Size	Mean (Baseline)	Std. Dev. (Baseline)	Mean (Test)	Std. Dev. (Test)	Pooled Std. Deviation	Computed t-Statistic	P-Value	Statistical Significance
MD-HI	Speed Variation in a Sublink (Shockwaves)	10%	5	13.31	0.55	12.52	0.45	0.3178	2.4858	0.037769	Yes
		25%	5	13.31	0.55	12.02	0.25	0.2700	4.7730	0.001403	Yes
		50%	5	13.31	0.55	11.54	0.37	0.2957	5.9837	0.000329	Yes
		75%	5	13.31	0.55	11.51	0.42	0.3098	5.8009	0.000405	Yes
		95%	5	13.31	0.55	11.45	0.22	0.2641	7.0559	0.000107	Yes
	Speed Variation Between Adjacent Sublinks	10%	5	12.81	0.48	11.78	0.47	0.2998	3.4355	0.008882	Yes
		25%	5	12.81	0.48	11.88	0.46	0.2979	3.1337	0.013938	Yes
		50%	5	12.81	0.48	10.91	0.20	0.2332	8.1411	3.85E-05	Yes
		75%	5	12.81	0.48	10.50	0.50	0.3084	7.4777	7.08E-05	Yes
		95%	5	12.81	0.48	10.48	0.45	0.2933	7.9481	4.58E-05	Yes
MD-HI-WW	Speed Variation in a Sublink (Shockwaves)	10%	5	14.00	0.44	13.36	0.37	0.2571	2.4893	0.037563	Yes
		25%	5	14.00	0.44	11.80	0.45	0.2805	7.8462	5.02E-05	Yes
		50%	5	14.00	0.44	11.26	0.46	0.2853	9.6054	1.15E-05	Yes
		75%	5	14.00	0.44	11.06	0.47	0.2889	10.1764	7.45E-06	Yes
		95%	5	14.00	0.44	10.99	0.21	0.2175	13.8415	7.17E-07	Yes
	Speed Variation Between Adjacent Sublinks	10%	5	13.02	0.36	12.20	0.27	0.2018	4.0638	0.003615	Yes
		25%	5	13.02	0.36	10.64	0.26	0.1986	11.9973	2.15E-06	Yes
		50%	5	13.02	0.36	10.11	0.35	0.2252	12.9090	1.23E-06	Yes
		75%	5	13.02	0.36	10.16	0.23	0.1906	15.0307	3.79E-07	Yes
		95%	5	13.02	0.36	10.03	0.25	0.1960	15.2778	3.34E-07	Yes
MD-NI	Speed Variation in a Sublink (Shockwaves)	10%	5	11.43	0.47	9.38	0.32	0.2543	8.0619	4.13E-05	Yes
		25%	5	11.43	0.47	8.90	0.22	0.2328	10.8848	4.49E-06	Yes
		50%	5	11.43	0.47	8.73	0.27	0.2433	11.0854	3.91E-06	Yes
		75%	5	11.43	0.47	8.63	0.22	0.2328	12.0268	2.11E-06	Yes
		95%	5	11.43	0.47	8.57	0.48	0.2998	9.5315	1.21E-05	Yes
	Speed Variation Between Adjacent Sublinks	10%	5	10.12	0.53	8.04	0.31	0.2755	7.5500	6.61E-05	Yes
		25%	5	10.12	0.53	7.37	0.27	0.2650	10.3924	6.36E-06	Yes
		50%	5	10.12	0.53	7.19	0.46	0.3141	9.3429	1.41E-05	Yes
		75%	5	10.12	0.53	7.24	0.45	0.3112	9.2673	1.49E-05	Yes
		95%	5	10.12	0.53	7.19	0.47	0.3177	9.2380	1.53E-05	Yes

Operational Condition	***Performance Measure***	***Market Penet-ration***	***Sample Size***	***Mean (Baseline)***	***Std. Dev. (Baseline)***	***Mean (Test)***	***Std. Dev. (Test)***	***Pooled Std. Deviation***	***Computed t-Statistic***	***P-Value***	***Statistical Significance***
HD-LI	Speed Variation in a Sublink (Shockwaves)	10%	5	14.19	0.12	14.00	0.32	0.1520	1.2500	0.246633	No
		25%	5	14.19	0.12	12.74	0.23	0.1156	12.5397	1.53E-06	Yes
		50%	5	14.19	0.12	11.58	0.26	0.1289	20.2269	3.73E-08	Yes
		75%	5	14.19	0.12	11.64	0.29	0.1420	17.9859	9.37E-08	Yes
		95%	5	14.19	0.12	11.56	0.25	0.1236	21.2368	2.54E-08	Yes
	Speed Variation Between Adjacent Sublinks	10%	5	12.84	0.21	12.41	0.32	0.1727	2.4903	0.037505	Yes
		25%	5	12.84	0.21	11.35	0.27	0.1540	9.6726	1.09E-05	Yes
		50%	5	12.84	0.21	10.61	0.32	0.1727	12.9245	1.22E-06	Yes
		75%	5	12.84	0.21	10.53	0.22	0.1363	16.9519	1.49E-07	Yes
		95%	5	12.84	0.21	10.46	0.46	0.2274	10.4476	6.12E-06	Yes

Table 6-7: Statistical Significance Test for MMITSS Application

Operational Condition	Performance Measure	Market Penet-ration	Sample Size	Mean (Baseline)	Std. Dev. (Baseline)	Mean (Test)	Std. Dev. (Test)	Pooled Std. Deviation	Computed t-Statistic	P-Value	Statistical Significance
MD-HI	Average Arterial Travel Time	10%	5	329.15	7.89	320.24	2.15	3.6569	2.4365	0.040788499	Yes
		25%	5	329.15	7.89	309.96	2.07	3.6476	5.2614	0.000763226	Yes
		50%	5	329.15	7.89	309.30	1.82	3.6215	5.4816	0.000586314	Yes
		75%	5	329.15	7.89	308.74	1.62	3.6019	5.6656	0.000472782	Yes
		95%	5	329.15	7.89	306.11	2.52	3.7037	6.2209	0.000253588	Yes
	Maximum Side-Street Queue	10%	5	511.53	13.20	517.12	9.23	7.2022	-0.7756	0.460305572	No
		25%	5	511.53	13.20	421.83	6.01	6.4857	13.8306	7.21775E-07	Yes
		50%	5	511.53	13.20	371.61	8.40	6.9964	19.9994	4.07495E-08	Yes
		75%	5	511.53	13.20	358.07	4.76	6.2759	24.4520	8.35438E-09	Yes
		95%	5	511.53	13.20	347.84	6.82	6.6448	24.6343	7.87807E-09	Yes
MD-HI-WW	Average Arterial Travel Time	10%	5	331.32	5.22	326.44	2.11	2.5176	1.9375	0.088683493	No
		25%	5	331.32	5.22	313.29	2.28	2.5476	7.0765	0.00010439	Yes
		50%	5	331.32	5.22	309.21	1.30	2.4061	9.1877	1.59184E-05	Yes
		75%	5	331.32	5.22	309.12	1.86	2.4782	8.9574	1.91888E-05	Yes
		95%	5	331.32	5.22	308.13	2.60	2.6078	8.8935	2.0225E-05	Yes
	Maximum Side-Street Queue	10%	5	505.46	14.70	447.86	16.00	9.7172	5.9273	0.00035079	Yes
		25%	5	505.46	14.70	340.86	19.97	11.0885	14.8445	4.17751E-07	Yes
		50%	5	505.46	14.70	214.45	8.50	7.5942	38.3197	2.36238E-10	Yes
		75%	5	505.46	14.70	202.18	14.55	9.2495	32.7885	8.16312E-10	Yes
		95%	5	505.46	14.70	151.64	14.48	9.2278	38.3431	2.35091E-10	Yes
MD-NI	Average Arterial Travel Time	10%	5	319.11	3.53	316.24	2.09	1.8346	1.5654	0.156109793	No
		25%	5	319.11	3.53	312.41	1.96	1.8048	3.7130	0.005930624	Yes
		50%	5	319.11	3.53	311.77	2.82	2.0211	3.6314	0.006671288	Yes
		75%	5	319.11	3.53	311.13	2.49	1.9311	4.1312	0.003293204	Yes
		95%	5	319.11	3.53	311.13	2.41	1.9115	4.1736	0.003106849	Yes
	Maximum Side-Street Queue	10%	5	454.42	12.56	353.99	12.71	7.9903	12.5693	1.50473E-06	Yes
		25%	5	454.42	12.56	218.12	13.78	8.3390	28.3364	2.59989E-09	Yes
		50%	5	454.42	12.56	107.53	15.99	9.0946	38.1419	2.45147E-10	Yes
		75%	5	454.42	12.56	99.97	4.72	5.9999	59.0755	7.48818E-12	Yes
		95%	5	454.42	12.56	95.43	4.85	6.0204	59.6290	6.95097E-12	Yes

Operational Condition	Performance Measure	Market Penet-ration	Sample Size	Mean (Baseline)	Std. Dev. (Baseline)	Mean (Test)	Std. Dev. (Test)	Pooled Std. Deviation	Computed t-Statistic	P-Value	Statistical Significance
HD-LI	Average Arterial Travel Time	10%	5	320.98	3.45	307.31	2.05	1.7956	7.6103	6.24446E-05	Yes
		25%	5	320.98	3.45	304.74	2.61	1.9341	8.3990	3.07115E-05	Yes
		50%	5	320.98	3.45	303.62	2.75	1.9736	8.7936	2.19713E-05	Yes
		75%	5	320.98	3.45	303.33	2.11	1.8081	9.7638	1.01439E-05	Yes
		95%	5	320.98	3.45	301.72	2.37	1.8724	10.2858	6.87519E-06	Yes
	Maximum Side-Street Queue	10%	5	511.53	13.42	499.46	9.28	7.2968	1.6544	0.136634057	No
		25%	5	511.53	13.42	314.99	9.28	7.2970	26.9348	3.88646E-09	Yes
		50%	5	511.53	13.42	248.03	5.13	6.4255	41.0081	1.37671E-10	Yes
		75%	5	511.53	13.42	255.77	1.62	6.0453	42.3078	1.0737E-10	Yes
		95%	5	511.53	13.42	245.53	11.81	7.9947	33.2717	7.2671E-10	Yes

6.3 Results Summary

As shown in the previous subsections, the benefits from DMA applications are dependent on the operational conditions in terms of demand in the system, weather conditions and induced incidents. In this chapter, we assessed INFLO, INC-ZONE and MMITSS applications, in isolation and in combination under different operational conditions. In addition, EnableATIS, FRATIS, and IDTO applications were assessed using the Phoenix testbed. A summary of the results in terms of different operational conditions that yield maximum benefits to specific application/combination is provided in Table 6-8. Table 6-9 shows the mapping of applications and their preferred facility types. The facility types have been identified based on the application's functionality and design.

Table 6-8: Applications/Combinations and their preferred operational conditions

Application/ Combination	***Operational Conditions that yield maximum benefits***
INC-ZONE	Medium demand and high incident severity yield maximum throughput for open lanes and high demand and low incident severity yield safer (maximum reduction in) speeds for vehicles in incident zones.
INFLO	Medium Demand/No Incident operational conditions yield maximum benefits in terms of reduction in shockwaves and speed variations.
MMITSS	Medium Demand/No Incident operational conditions yield maximum benefits in terms of reduction in side-street queues, and medium demand with high incident severity yield maximum benefits in terms of arterial travel time.
EnableATIS	High demand, medium incident severity, and wet weather operational conditions provided maximum benefits in terms of travel time saved.
FRATIS	High demand and high incident severity provided maximum benefits in terms of truck travel time.
IDTO	Low demand and low incident severity provided maximum benefits in terms of travel time saved for transit passengers.
INFLO+INC-ZONE	High demand and low incident severity provided maximum benefits in terms of two of the safety-based performance measures, namely reduction in shockwaves and reduction in speeds at the incident locations.
INC-ZONE+MMITSS	Medium demand and high incident severity provided maximum benefits in terms of average network speed and delay.
INFLO+MMITSS	Medium demand and high incident severity provided maximum benefits in terms of average network speed and delay.

Table 6-9: Applications evaluated for different facility types.

Application	Favorable Facility Type	Reasoning
INC-ZONE	Freeway	INC-ZONE application aims at delivering alerts about incidents ahead using CV technology with one of the most important aspect being threat determination. The application uses the vehicle location to identify whether the incident location is along the vehicle's path in terms of lane and heading. This is easier in a freeway setting due to the wider geographic range of the road.
INFLO	Freeway	INFLO application harmonizes speeds of vehicles on a roadway and hence is better deployed on freeways. Arterial traffic could get intermittent stops depending on the intersection control in place.
MMITSS	Arterial	MMITSS application aims at optimizing the signal control which is not present in a freeway setting.
EnableATIS	Freeway/Arterial	EnableATIS uses information on travel-time, travel-speeds, incidents etc. to provide pre-trip and en-route advisories to equipped vehicles and is therefore favored in both arterials and freeways.
FRATIS	Freeway/Arterial	FRATIS application is an enhanced form of traveler information system and is therefore used in both arterials and freeways.

Chapter 7. Messaging Protocols

This chapter primarily deals with the research questions that are based on the usability of different messaging protocols with different DMA applications. Specifically, two research questions have been identified to determine the impact of messaging protocols on the applications. The results provided in this chapter are qualitative in nature and are based on available literature on the messaging protocols and the way applications are currently modeled for this project. Messaging protocol requirements were determined by comparing the different communication attributes of the prototyped applications such as messaging frequency, data elements, latency etc. using a qualitative assessment performed by the team. Please note that the applications utilized in this chapter reflects the versions that are modeled for AMS testbed modeling and may be different from field implemented versions of the applications.

7.1 Research Questions and Hypotheses

The following research questions are answered in this chapter:

1. Is SAE J2735 BSM Part 1 transmitted via Dedicated Short Range Communications (DSRC) every 10th of a second critical for the effectiveness of the DMA bundles? Will alternate messaging protocols, such as Probe Data Message (PDM), Basic Mobility Messages (BMM), etc., suffice? Given a set of specific messages, what combinations of bundles have the most benefit? Conversely, given a specific combination of bundles, what messages best support this combination?
2. To what extent are messaging by pedestrians, pre-trip, and en-route (e.g., transit riders) travelers critical to the impact of individual bundles or combinations of bundles? Does this criticality vary by operational condition?

In order to answer these, the following hypotheses were made.

1. BSM Part 1 data transmitted every 10th of a second via DSRC is not critical for the effectiveness of DMA applications, with the exception of CACC. DMA bundles will be more effective with alternate messaging protocols in addition to BSM Part 1.
2. Bundles that most significantly influence or are impacted by travelers' trip making decisions (EnableATIS, IDTO) or pedestrian movements (MMITSS, R.E.S.C.U.M.E.) will have the most critical need for messaging by pedestrians, and pre-trip and en route travelers. This criticality will vary by operational condition.

7.2 Analysis Approach and Findings

Based on the application description and functionality, the tactical DMA applications (such as INFLO, MMITSS and R.E.S.C.U.M.E.) require localized low latency communication delivering fixed message sets which could be possible using standardized data sets such as BSM, BMM and PDM. However, the strategic applications (such as EnableATIS, IDTO, and FRATIS) are wide-area applications that could work off higher latencies. In addition to this, strategic applications require and deliver dynamic, market-driven contents which require message sets beyond the scope of standardized data elements. These message data elements are enlisted in Appendix B. In order to analyze how effective each message type (BSM, PDM, BMM) are for the DMA application bundles, it is important to look at the basic characteristics of each, and compare with the requirements of each application under study. It is also important to know the characteristics of dedicated short range communication (DSRC) network features, as it is the envisioned medium of broadcast of these messages[28].

At a high-level, DSRC is the wireless communication protocol for the vehicles based on the Wireless Fidelity (Wi-Fi) architecture. However, in order to support high-speed moving vehicle and simplify the mechanisms for communication group, IEEE working group has developed the Wireless Access in Vehicular Environments (WAVE) concept that is the core of the DSRC[29]. WAVE is an enhanced to the IEEE 802.11 standard, also known as IEEE 802.11p to support the ITS applications in the short-range communications. This includes data exchange between high-speed vehicles and between the vehicles and the roadside infrastructure in the licensed ITS band of 5.9 GHz (5.85-5.925 GHz), a 75 MHz bandwidth. With the equipment installed in the car and on the road, WAVE has the potential to supply the real time traffic information, improve the safety of the transportation, and keep the information secure.

There are multiple messaging protocols envisioned at this time to support connected vehicle applications. Some of them, utilized in the DMA applications[30], are given below:

1. **Basic Safety Message (BSM)** is a message protocol that allows connected vehicles to broadcast their information at 10 Hz rate continuously and is tailored for low latency, localized broadcast required by V2V safety applications. It contains the following vehicle information: location (latitude, longitude, elevation), heading, speed, 4-D acceleration (latitudinal, longitudinal, vertical, yaw), brake status (brake applied for each wheel, traction control state, ABS state, stability control state, brake boost applied, auxiliary brake status), and vehicle size (length, width). BSM is typically a vehicle-to-vehicle message; however, it can be received by the RSE to provide additional vehicle probe data to the infrastructure. BSM has a Part 2, which has event-driving data elements such as ABS activation and is transmitted less frequently.
2. **Probe Data Message (PDM)** represents a snapshot of the vehicle at 1-second interval and is broadcasted when within the range of a Road Side Equipment. These messages are stored until the vehicles are within the range of a Road Side Equipment and are sent from the infrastructure to vehicles to specify (non-default) vehicle probe data frequencies, regions, and event thresholds. PDMs are generally used for V2I communication for probe-vehicle applications.
3. **Basic Mobility Messages** are the messages that include data elements identified for mobility applications (such as the DMA applications) and are not defined in the SAE J2735. This message is identified in the FHWA-JPO-13-065 report along with the candidate data elements based on individual applications. This report, however, defines the candidate elements based on the prototyped applications.
4. **Signal Phase and Timing Message (SPaT)** includes the current movement state of each active phase and values from which the on board equipment (OBE) can project the duration of the permissive phase (unless it is changed by an event such as preemption). SPaT is generally used by signal-based applications such as Red-Light Violation Warning, Left/Right Turn Assist etc. These applications use MAP messages to identify the lane, intersection and signal structure.

[28] http://www.its.dot.gov/factsheets/dsrc_factsheet.htm
[29] https://www.standards.its.dot.gov/factsheets/factsheet/80
[30] McGurrin. M, Vehicle Information Exchange Needs for Mobility Applications Exchange: Version 3.0, FHWA-JPO-13-065

The connected vehicle environment also uses other types of data such as MapData to communicate the intersection or roadway configuration of on-coming vehicles, Signal Request Message to communicate a preemptive, or priority request from a connected vehicle to the signal controller and other forms of message types.

The main purpose of DMA applications is mobility and therefore may not require high rate messaging such as BSM. In order to assess this and the suitability of alternate messaging protocols such as Probe Data Message, Basic Mobility Message in fulfilling the data needs of applications, the application requirements in terms of specific frequency, data elements and latency that is required in the prototyped application is used to list acceptable messaging protocols for each application. Table 7-1 lists the basic data elements that are required by the modeled applications. Please note that several other data elements are required in terms of the System Design and these elements are listed in Appendix B.

Table 7-1: Data elements required by tactical applications as used in simulation

Application (Bundle)	*Data Elements Required by the Prototype*	*Frequency*	*Acceptable Messaging Protocols*
Q-WARN (INFLO)	• Speed and Acceleration • Position (Local 3D) • Queued Condition	20 seconds	BSM BMM PDM
SPD-HARM (INFLO)	• Current Lane • Speed and Acceleration • Position (local 3D) • Target Speed • Target Lane	20 seconds	BSM BMM PDM
INC-ZONE (R.E.S.C.U.M.E.)	• Current Lane • Speed and Acceleration • Position (local 3D) • Target Speed • Target Lane	1 second	BSM BMM PDM
RESP-STG (R.E.S.C.U.M.E.)	• Current Lane • Target Lane • Target Speed • Speed and Acceleration • Position (local 3D)	1 second	BSM BMM PDM
MMITSS – All Applications	• Position (local 3D) • Speed and Acceleration • Vehicle Type	0.1 second	BSM

Please note that the frequency of data sources is sourced from the respective application's Impact Assessment reports as given below:

1. Impact Assessment of Dynamic Speed Harmonization with Queue Warning (FHWA-JPO-15-222).

2. 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) (FHWA-JPO-15-203).
3. Multi-Modal Intelligent Traffic Signal Systems (MMITSS) Impacts Assessment (FHWA-JPO-15-238)

As indicated, BSM can satisfy the frequency and data element requirements of all the listed applications. However, other messages (BMM and PDM) that are broadcasted less frequently could also satisfy those requirements (except of MMITSS application bundle which require a localized, low-latency messaging). For BSM part I, 10 Hz message rate has been dedicated, but as far as these applications are concerned, the 10 HZ frequency is not required for most of them. Moreover, 10 Hz may not be necessary when there is high volume of traffic (and as a result network congestion) as the vehicles are moving at a much lower speed and hence do not require other vehicles basic information update as frequently.

On the other hand, non-BSM messages (i.e. BSM Part II, BMM etc.) do not need to be transmitted as frequently as BSM Part I because the information they contain is not as critical. It is evident that both BMM and PDM messages which are broadcasted less frequently are suitable to be utilized for majority of the applications and high BSM message rate is not necessary for the DMA bundles that are the focus of this study.

7.2.1 Criticality of En-route and Pre-Trip Messaging

Pre-trip and en-route messaging is used in the EnableATIS application to enable dynamic routing of vehicles based on the link travel time. Travelers with “pre-trip” messaging capability will choose their routes based on the trip’s start time and will remain the same through the course of their travel. Travelers with “en-route” messaging capability will update their route preferences in real-time by monitoring the traffic conditions in the network. Please note that the EnableATIS application modeled in this chapter only affects routing of vehicles. In order to assess the criticality of en-route and pre-trip messaging on the EnableATIS application performance, different levels and combinations of equipage and en-route/pre-trip messaging was utilized in the analysis. The results are shown in Figure 7-1, where the Do Nothing travel time and distance for the Phoenix network for the High Demand and Low Incident severity operational condition is compared to cases where there is VMS, pre-trip and en-route messaging. An assessment of other operational conditions is provided in Section 6.2.4.

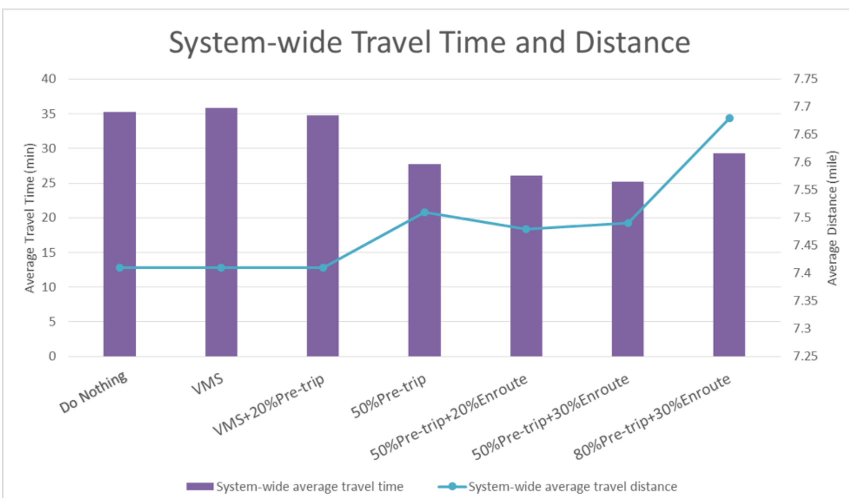


Figure 7-1: EnableATIS Performance under Pre-Trip and En-Route Messaging [Source: Booz Allen]

As shown, the EnableATIS system increases the travel distance of vehicles, since they have to take alternate routes to avoid congestions on their way. The legacy VMS systems may increase the system-wide travel time even though it can relieve the severity of congestions at bottlenecks. It is because VMS can only reroute vehicles to other routes without considering the system-wide impacts and those rerouted vehicles may create additional congestions at other locations. In contrast, EnableATIS solution will reallocate vehicles' routes systematically and not only relieve the congestions at bottlenecks but also the whole system.

Since with EnableATIS market penetration increase, delays increases, it would be reasonable to focus on improving the accuracy of traffic state prediction and systematically optimize many vehicles' routes together in the context where there is a high market penetration rate of EnableATIS in the future. Given the current accuracy of traffic state prediction and system modeling and optimizing capability, EnableATIS will reach its maximal benefits when 50 percent of travelers reply on pre-trip information and 30 percent of travelers using their on-board devices to receive real-time routing information. This may also be because pre-trip travelers do not re-optimize the routes once the trip is started and may result in new bottlenecks during the course of their travel.

7.3 Results Summary

This chapter demonstrates the mapping of different messaging protocols, such as BSM, BMM, and PDM to support different applications to assist in a qualitative assessment of which messaging protocols are optimal to each application. The mapping was based on the input requirement for each of the modeled application. Please note that the actual input requirement might vary and a full list of inputs are provided in Appendix B along with the supporting messaging protocol.

The prototyped INFLO and INC-ZONE applications can work input update rates that are less than 10 Hz. The prototyped MMITSS application requires BSM messages at 10 Hz frequency to work. Pre-trip and en-route messaging is critical for strategic applications such as EnableATIS.

Applications such as INFLO (SPD-HARM and Q-WARN) and INC-ZONE require messaging at a much longer frequency than 10Hz since they act on a wider area. For example, SPD-HARM application acts along a freeway corridor and CV data is only used to identify harmonized speeds over sections of freeway at a minimum resolution of 5 miles per hour with an update frequency of 20 seconds. Therefore, messages such as BMM or PDM can be used in lieu of BSM messages. The MMITSS application, however, is much more localized. From the application design, it is evident that the BSM messages are instantly used to place advanced calls to the detector phases and it is imperative that these messages are delivered at lowest latency and fastest frequency. Therefore, BSM messages are critical for this application. Our hypothesis that only some application would require messaging at 10Hz frequency is therefore true.

Criticality of en-route or pre-trip messaging was assessed using EnableATIS through simulations that represented different market penetration of VMS equipage, en-route, and pre-trip route optimization. The results indicate that the en-route messaging is important in leveraging all of the benefits of the application. With just pre-trip messaging, travelers may not have access to the most optimum routes based on changing traffic conditions. Pre-trip and en-route messaging also indicated higher travel distance, but the travel time was always lower than the baseline.

Chapter 8. Communication Technology

This chapter summarizes the communication technology required for individual DMA applications and bundles and compares the suitability of Dedicated Short Range Communication (DSRC) and cellular communication. A full-fledged communication modeling using software such as OPNET or Riverbed Modeler was not included as part of this project and therefore, the team conducted quantitative analysis to understand the different research that is being done as part of the envisioned CV media. Please note that the applications utilized in this chapter reflects the versions that are modeled for AMS testbed modeling and may be different from field implemented versions of the applications.

8.1 Research Question and Hypothesis

Specifically, this chapter addresses the following research question:

- Will a nomadic device that is capable of communicating via both DSRC as well as cellular meet the needs of the DMA bundles? When is DSRC needed and when will cellular suffice?

In order to answer this question, the hypothesis suggested is that nomadic devices that are capable of communicating via both DSRC as well as cellular will meet most of the needs of the DMA applications; however, additional data from the infrastructure will be required for DMA applications to be effective. DMA applications, with the exception of component applications of the INFLO and MMITSS bundles, will not need data to be transmitted via DSRC as higher-latency communications media (e.g., cellular) will suffice. Please note that Chapter 7 deals with message type (in-terms of frequency and data elements) whereas this chapter deals with the technology, in terms of latency and range.

8.2 Analysis Approach

For this assessment, the key differences between DSRC-based and cellular-based communication has been identified. DSRC communication is widely envisioned as the primary connected vehicle medium for safety applications due to its low-latency, high-reliability performance. However, non-safety applications, such as the DMA applications, need not rely on low-latency communication, but a widespread cellular communication.

Table 8-1: Characteristics of DSRC and Cellular Communication

Communication Attributes	*DSRC*[31]	*Cellular (LTE)*
Range	100~1000 meters	Kilometers
Data Rates	6 to 27 mbps	50-300[32] mbps
Latency (round-trip)	200 Microsecond	Less than 5[33] millisecond

Table 8-1 shows a comparison of the characteristics of DSRC and cellular communication in terms of three key differentiators:

1. Distance Range: DSRC works at a much shorter range than cellular. Since most DMA applications utilize V2I communication, a shorter range will translate to more localized application functionality. Therefore, wide-area applications such as Speed Harmonization will require a dense network of Roadside Equipment for its support.
2. Data Rates: DSRC's data rates are less than cellular communication due to limited channel availability. This may cause channel congestion during high traffic densities. A high traffic density on road leads to high interference in the communication channels. This high interference results in a poor packet success probability which means that the host vehicle does not receive information and retransmission to host vehicle has a similar probability of failure with an added time delay.
3. Communication Latency: One of the primary advantage of DSRC is its low latency, which is critical to safety applications. Cellular networks' latency is expected to go down to match DSRC's with the introduction of 5th Generation networks, or 5G. But cellular networks are also noted to have lower reliability to be able to be used for safety applications. However, it is a good alternative for mobility-based applications.

In order to assess the suitability of DSRC and cellular communication with individual DMA applications, the application requirements are compared with the communication attributes such as range, data rates, and latency. DSRC presents a low-latency medium of communication and is required for safety applications. However, DMA applications could work on higher latencies. Specifically, this section deals with the suitability of application and its system design under different communication types.

8.2.1 INFLO Applications

The INFLO application that constitutes both SPD-HARM and Q-WARN works at a facility level on freeways and the harmonized speed and queue notifications are specific to sublinks (defined as a 0.5-mile section of a freeway). Individual sublink's target speed and queue determination is done using inputs from the connected vehicles in the same sublink at a frequency of 5 to 20 seconds. Hence, cellular communication can be better utilized for this set of applications owing to its widespread coverage (throughout the freeway facility), sub-second latency, and high data rates (urban freeways are subjected to heavy traffic). The cellular network may provide a better medium given that they cover a bigger range than DSRC. On the other hand, the low latency of DSRC may not be as needed for INFLO applications

[31] Accessed: http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=5888501
[32] Depending whether it is uplink or downlink; 3rd generation Partnership Project (3GPP): Accessed: http://www.3gpp.org/technologies/keywords-acronyms/98-lte
[33] Cellular Network latency is in order of 100-500 milliseconds but LTE provide a better latency.

because the frequency of the updates (for the prototype application) is in the range of 20 seconds, much higher than a typical LTE network latency (less than 5 milliseconds).

However, for the CACC applications, DSRC is the preferred medium owing to its low-latency requirement and V2V functionality. CACC works between two vehicles in a closed range and lower latency can yield better performance due to lesser headway.

8.2.2 R.E.S.C.U.M.E. Bundle

The prototyped INC-ZONE and RESP-STG applications that constitute this bundle primarily works on the incident region, specifically 1000 to 2000 feet upstream of an incident. Also, vehicles receive specific alerts and warnings according to their distance from the incident, current lane, and current speed. This makes the applications require communications that are low-latency and localized, so that they receive the alerts specific to their location immediately. This makes DSRC network the best candidate, although it does not include cellular networks. The cellular network, specifically LTE, can still satisfy the range and latency requirements of these applications.

8.2.3 MMITSS Bundle

Similar to INC-ZONE application, MMITSS bundle and applications are localized to the intersection and aims at using CV data to place advanced calls on the controller phases. This means that low latency is critical to the applications functioning. In addition, since the application is local to signalized intersections, a wider range of geographic coverage is not very critical in the application. These factors combined with ease of localizing the data broadcast and usage makes DSRC, a better choice for MMITSS application. Additionally, the range of DSRC equipment is good enough for vehicles within an intersection being identified and detected for signal-call placement.

8.2.4 EnableATIS and FRATIS Bundles

EnableATIS is a strategic application bundle that works over an entire regional network and utilizes the link-travel times to optimize the vehicle’s routing behavior. The applications under EnableATIS do not require low-latency communication medium, since the link travel times are updated at 1 to 5 minute intervals for en-route travelers. Therefore, cellular network can suffice DSRC owing to its wider coverage and the ability to transmit large amounts of data, when there is system congestion and when the market penetration is higher.

FRATIS application is similar to the EnableATIS bundle which works at a network-level and does not require low-latency, localized communication.

8.2.5 IDTO Bundle

IDTO is a strategic application bundle that works over an entire transit network to find best transit alternative and connections for transit users. This makes the range of communication required to be wide-area and the latency to be not very important. In addition, travelers will be using cellular devices to receive and send alerts and requests. Therefore, cellular devices and other non-DSRC based media would be sufficient for this application/bundle.

8.3 Results Summary

For localized and safety-critical applications, low-latency communication with neighboring devices is critical; this favors direct V2V communication through a simple medium access control protocol. DSRC (approximately 200 microsecond) would certainly fare better compared to LTE (below 5 millisecond). However, the DMA bundle applications are focused on mobility and could afford higher latency mediums. Moreover, with comparatively better latency of 4G and promise of 5G, latency issue of cellular could be easily addressed. Given that the rate of communication update required for most DMA applications is more than 0.1 second, both DSRC and cellular could satisfy the requirement and latency risk could be minimized.

DSRC is favorable for applications at a localized area that require low-latency, such as MMITSS and INC-ZONE. Applications such as SPD-HARM, Q-WARN, and EnableATIS would work with cellular communication owing to its wider coverage and larger update frequency. Nomadic devices capable of both cellular and DSRC will be a good choice for DMA applications due to this mix.

From the above analysis, a nomadic device capable of communicating via DSRC and cellular will be very useful for DMA applications. As summarized in Table 8-2, certain applications/bundles that require localized deployment works best using DSRC, whereas others prefer cellular. Most DMA applications, with the exception of CACC, do not rely on the low-latency characteristic of DSRC since; they can afford to have a sub-second latency.

Table 8-2: Summary of Preferred Medium for DMA Applications.

Applications (Bundle)	Preferred Medium
SPD-HARM (INFLO)	Cellular is better due to wide coverage requirement.
Q-WARN (INFLO)	Cellular is better due to wide coverage requirement.
CACC (INFLO)	DSRC is required due to V2V safety aspect.
MMITSS Bundle	DSRC is better because deployment is generally localized
INC-ZONE (R.E.S.C.U.M.E.)	DSRC is better because deployment is generally localized
RESP-STG (R.E.S.C.U.M.E.)	DSRC is better because deployment is generally localized
EnableATIS Bundle	Cellular is better due to wide coverage requirement.
FRATIS Bundle	Cellular is better due to wide coverage requirement.
IDTO Bundle	Cellular is better due to wide coverage requirement.

Chapter 9. Communication Latency

The AMS testbeds also feature advanced communications emulator to assess some of the communication-related sensitivity analysis as far as connected vehicle applications are concerned. Please note that the communications modeling performed within the scope of this project does not assume physical characteristics of wireless communication such as channel congestion, environmental impacts, hidden nodes, retransmission etc. Primarily, San Mateo testbed was used to assess the impact of communication latency and losses on application performance by interfacing TCA communications emulator[34] and MMITSS BSM emulator. These emulators were used to generate BSM messages for applications so that analysis could be done using different levels of communication latency and loss rates. TCA tool, developed by Noblis, was used in conjunction with INFLO and INC-ZONE applications. MMITSS application uses its built-in communications emulator which was modified to replicate some of these advanced functionalities (e.g., latency affects). Strategic applications that are assessed using the Phoenix testbed are not assessed using these communication models. Please note that the applications utilized in this chapter reflects the versions that are modeled for AMS testbed modeling and may be different from field implemented versions of the applications.

9.1 Research Questions and Hypotheses

This chapter addresses the following research questions:

1. What are the impacts of communication latency on benefits?
2. How effective are the DMA bundles when there are errors or loss in communication?

The following hypotheses were made to design this analysis:

1. As communication latency increases, benefits will decrease. Most significant decrease will be observed for applications that require higher update frequency such as MMITSS and INC-ZONE.
2. The Effectiveness of some DMA bundles will be more impacted than others due to errors or loss in communication. MMITSS and INC-ZONE will be most impacted by errors or loss in communication.

Tactical applications such as INFLO, MMITSS, and INC-ZONE uses V2V and V2I communication and are expected to be more sensitive towards latency and loss in communication. Therefore, these applications were evaluated under different communication attributes of latencies and losses.

9.2 Analysis and Research Findings

In order to evaluate the impact of communication latency and losses on tactical DMA applications, the team developed a simulation setup with three layers as shown in Figure 9-1. The three layers are:

1. **Traffic simulation layer:** For the San Mateo network, Vissim was used for simulating the traffic

34 http://www.its.dot.gov/meetings/v2i_webinar.htm

in a time-step based progressive way. At each time-step, the simulation is stopped by the application manager and reads data from the simulation and redefines attributes in the simulation. The application manager uses Vissim's inherent COM scripts to read data and set attributes.

2. **Communications layer:** This layer, as denoted by the TCA BSM Emulator or MMITSS BSM Generator, uses the data generated from the simulation at every time-step and converts them into BSM messages using preset values of latency and losses. For example, if a latency of 1 second is set for the communications layer, these tools will delay the delivery of BSM messages by 1 second. TCA BSM Emulator uses COM-based scripts that are integrated with the application manager to read data from the simulation. MMITSS BSM Generator uses Vissim Driver Behavior Models to communicate the vehicle reports from Vissim.
3. **Applications layer:** The application layer receives the BSM messages from the communications layer based on communications attributes set by the modeler. Once the application receives the data, it generates specific output "commands" for different components of the simulation and is communicated back to the simulation. Please note that the communication attributes, such as latency and losses, are incurred only during the V2I communication (assuming that the applications reside on the Infrastructure). No communication attribute has been assigned to the I2V communication.

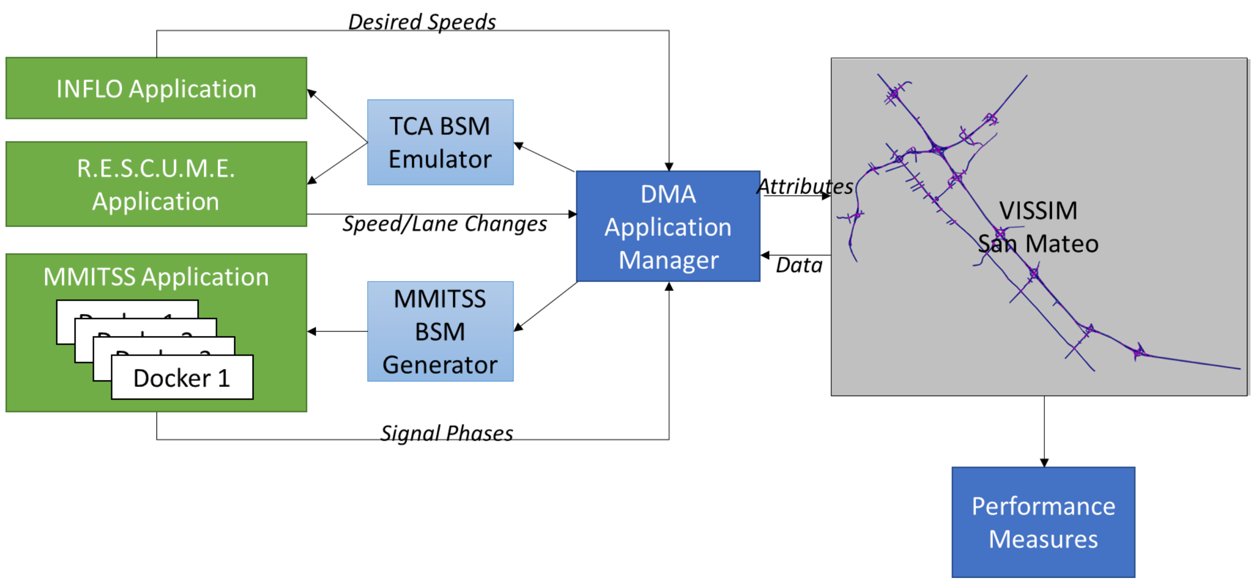


Figure 9-1: San Mateo Network Setup Showing Communications Emulator Set Up [Source: Booz Allen]

9.2.1 INFLO Applications

In order to assess the impact of communication latency and errors, San Mateo network was simulated using INFLO application under varying latency and loss rates which are inputs to the TCA model. The TCA model was equipped to generate BSM messages over a ubiquitous cellular network covering the entire US-101 freeway. Therefore, all "connected vehicles" in the freeway will generate BSM messages. When a latency is induced into the system, the value is added to the transmission time for each message. For the loss rate, the TCA determines if the message is lost by generating a random percentage and if that percentage is less than the lost rate the message is not transmitted.

Due to the complexity of TCA model and the size of the San Mateo network, simulations using the TCA tool were running at 0.2 times the real time speed. Hence, simulations were limited to the peak hours, representing 3:30 pm to 6:30 pm, and the results were aggregated over a 1-hour simulation time (4:30 pm to 5:30 pm), which uses TCA-INFLO set up to run. The medium demand/no incident operational condition was used in this analysis with a CV market penetration of 50 percent. Four different latency values were used in this analysis ranging between 0 seconds and 5 seconds.

Figure 9-2 shows the reduction in shockwaves and speed variations at different latency values. Latency values of 1, 3, and 5 seconds were used to do sensitivity analysis. Values less than 1 second were not used since the simulation resolution was reduced to 1 second to achieve a performable simulation speed. As shown, INFLO reduces the shockwaves by up to 8 percent and speed variations by up to 20 percent under these operational conditions. As communication latency increased, these reductions decreased. There was a drastic reduction in speed variations even for a 1-second latency, but the shockwave reduction was marginal. At 3-second and 5-second latencies, the impact of INFLO on shockwaves was marginal.

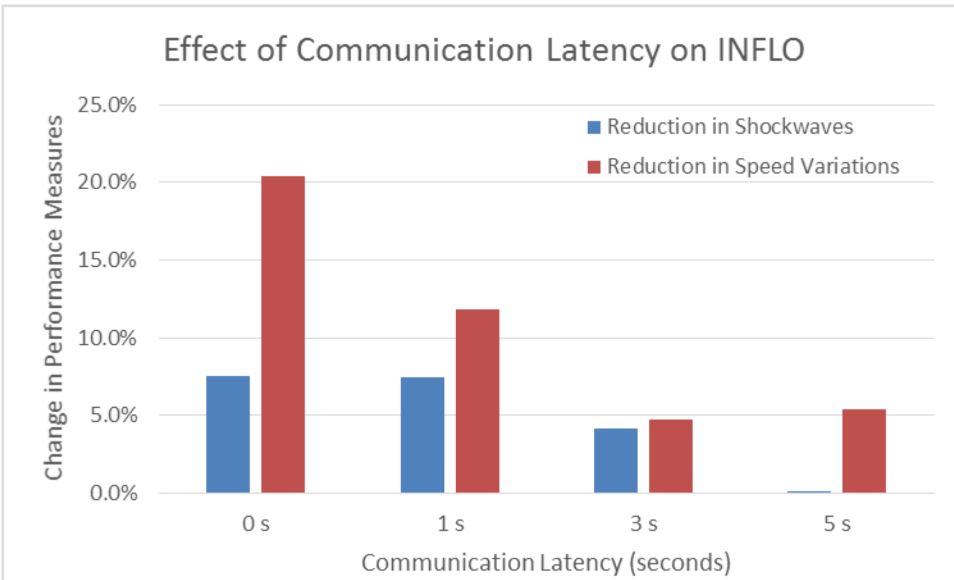


Figure 9-2: Reduction in Shockwaves due to INFLO under Different Latencies [Source: Booz Allen]

A similar assessment was done to test the sensitivity of the applications with respect to communication loss. The team assessed the impact of 10 and 20 percent average communication loss in terms of shockwave and speed variation reductions and the results are shown in Figure 9-3. Values higher than 20 percent were not used in the assessment because the packet-error rate will be under 20 percent with ubiquitous DSRC or cellular coverage[35]. As shown, the reduction in shockwaves and speed variations without any loss were 8 percent and 20 percent respectively. This reduction was greatly affected by communication losses. An average 10 percent loss reduced these values to 5 percent and 18 percent respectively. For losses over 20 percent, the impact of INFLO was negligible in terms of shockwave reduction.

[35] Andrews, S and Cops, M, *Final Report: Vehicle Infrastructure Integration Proof of Concept Technical Description –Vehicle*, FHWA-JPO-09-043

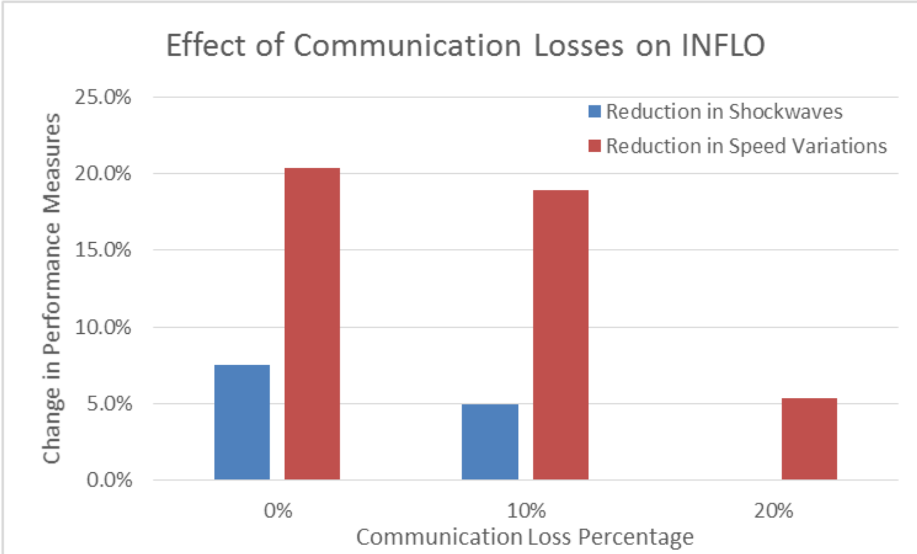


Figure 9-3: Reduction in Shockwaves due to INFLO under Varying Loss Rates [Source: Booz Allen]

9.2.2 INC-ZONE Application

INC-ZONE application was also integrated with capturing inputs from TCA tool under predefined latency values. For this analysis, the San Mateo testbed was used with localized CV broadcast within 2000 feet of the incident for the Medium Demand and High Incident operational condition at 50 percent market penetration. The two performance measures captured are reduction in average speed of vehicles in the incident zone (improving the safety of vehicles and personnel at the incident location) and increase in average throughput of the open lanes (improving the mobility of the network). Latency is more critical to INC-ZONE than INFLO owing to the fact that INC-ZONE is a localized application and the zones for "Warning", "Alert" and "Advisory" are much smaller than the length of sublinks (in the context of INFLO). Hence, the sensitivity was assessed using 1-second and 2-second latencies.

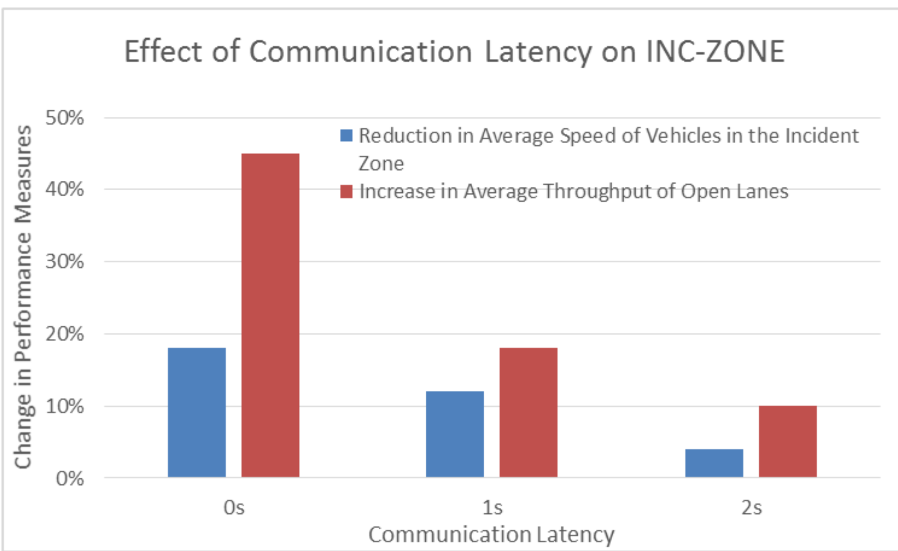


Figure 9-4: Change in Performance Measures due to INC-ZONE Latency [Source: Booz Allen]

As shown in Figure 9-4, latency has significant impact on the performance of INC-ZONE. For example, the average reduction in speed of vehicles in the incident zone reduces from 18 percent to 12 percent with just 1-second latency in communication. This is notably due to vehicles passing from advisory zone to warning zone and warning zone to alert zone in the time it receives the alert. Similarly, the increase in incident zone throughput reduces from 45 percent to 18 percent when the latency is 1 second. Latency values beyond 2 seconds significantly impact the performance of the application with respect to both a reduction in average speed (4 percent) and an increase in average throughput (10 percent).

It was seen that communication losses and lowering market penetration had similar impacts, since communication losses are just reduction in number of vehicles broadcasting data. For example, a 10 percent loss in communication when there is 50 percent market penetration was similar to a market penetration of 45 percent.

9.2.3 MMITSS Application

MMITSS Application uses its own communications emulator, developed by University of Arizona, which uses Vissim's built-in Driver Behavior Model to collect vehicle attributes from the simulation. The emulator distributes this data to specific RSE-modules within the MMITSS application based on the location of vehicles. The team modified this tool to add a user-specified communication latency that delays the delivery of messages to the RSE-based soft controllers. The MMITSS bundle, specifically, I-SIG was assessed under different latency rates of 0.5-second, 1-second and 1.5-second using this function for the Medium Demand/No Incident operational condition with 50 percent vehicles generating BSMs. The results are shown in Figure 9-5, where the change in arterial travel time is shown as a percentage deviation from the baseline.

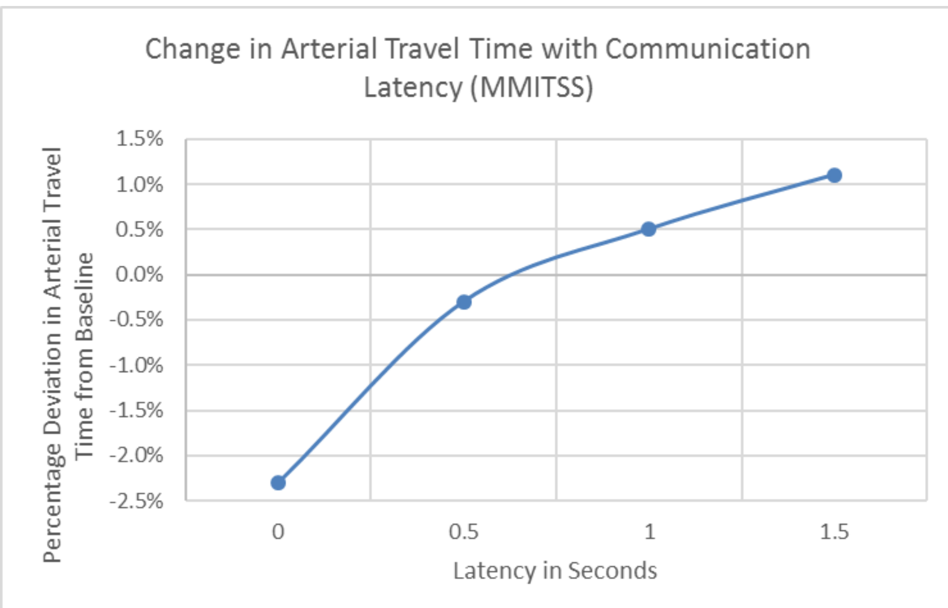


Figure 9-5: Change in Arterial Travel Time with MMITSS under Communication Latency [Source: Booz Allen]

As shown in Figure 9-5, the MMITSS benefits reduce drastically with increase in latency, much more than INFLO and INC-ZONE. At 0.5-second latency, the reduction in arterial travel time decreases from 2.8 percent to almost 0.2 percent. The application showed dis-benefits when the latency was 1 second or higher where the travel time increased when there was significant latency in communication. This is probably owing to the fact that the MMITSS is placing late calls for signal phase change which at times result in phase switches after the vehicle leaving the intersection. For example, the MMITSS application will request switching green-phase to the side street, but due to the communication latency, the controller might have already switched the phase allowing a longer-than-required green phase. Impact of communication losses were similar to INC-ZONE, where communication losses translate to a reduction in market penetration

9.3 Results Summary

As demonstrated in Section 9.2, communication latency and losses significantly affect the performance of applications. This chapter assessed the impact of these communication attributes on INFLO's speed harmonization and queue warning, R.E.S.C.U.M.E.'s incident zone alerts application and the MMITSS bundle. INFLO was assessed for reduction in shockwaves and speed variations and showed that latency values beyond 3 seconds deteriorated the application performance by more than 50 percent, whereas losses beyond 10 percent virtually had zero benefits on shockwave reduction. INC-ZONE application's assessment showed that it is more sensitive to latency with almost 60 percent benefits being lost with 1-second latency. MMITSS had the highest impact due to communication latency, since it had a higher update frequency when compared to INFLO and INC-ZONE. Even a 0.5-second latency deteriorated MMITSS's benefits by over 90 percent and higher latencies caused disbenefits to the system. The impact of communication losses in INC-ZONE and INFLO were similar to reduction in market penetration.

DMA application's performance deteriorates significantly with increase in communication latency and loss-rates. Latency had the highest impact on MMITSS, followed by INC-ZONE and INFLO applications. Strategic applications were not assessed for sensitivity to communication attributes.

Chapter 10. RSE/DSRC Footprint

This chapter conducted a qualitative analysis of the benefits of different communication technologies and RSE/DSRC footprint on the different DMA applications.

10.1 Research Questions

The following research questions will be answered in this chapter.

1. What are the benefits of widespread deployment of DSRC-based RSEs compared with ubiquitous cellular coverage?
2. Which technology or combination of technologies best supports the DMA bundles in terms of benefit-cost analysis?

In order to assess these, the following hypotheses were made:

1. In comparison to widespread cellular coverage, widespread deployment of DSRC-based RSEs will be excessive for DMA bundles. Concentrated deployment of DSRC-based RSEs will be more cost-beneficial in highly congested urban areas than in non-urban or low to moderate congested urban areas.
2. More cost-effective benefits will be observed when connected vehicles transmit and receive messages using dual mode communications (e.g., both DSRC and cellular).

The benefit-cost analysis tools used could not compare cellular and DSRC deployments since the cost model was constrained to only DSRC-based communication. Hence question 2 is not included in this evaluation.

10.2 Analysis Approach

Cellular networks and DSRC-based networks with Roadside Equipment (RSE) are different in their coverage. While cellular networks provide low-cost coverage to a larger area, DSRC-based networks offer low-latency concentrated coverage within 250 to 300 meters of a deployed RSE. Hence preferring one over the other depends on individual application's requirements. In order to assess this, the team conducted a qualitative analysis of these two technologies based on available literature.

10.2.1 Dedicated Short-Range Communication:

DSRC is a short to medium range communication technology which allows high-speed communication between vehicles and the infrastructure or between vehicles owing to its low-latency characteristics. The benefits of a complete deployment of a DSRC-based network with Roadside Equipment (RSE) are as follows:

1. DSRC has a dedicated bandwidth for solely vehicular communication
2. Provides low-latency communication which is essential for a safe vehicular network

3. A DSRC network complemented by RSEs provides a comprehensive network where most benefits of a fully connected vehicle and infrastructure network could be obtained
4. It works for both rural and urban settings
5. There has been already much research and development conducted on DSRC for V2V and V2I communication

However, DSRC has some shortcomings and some of them are listed below:

1. DSRC has a limited bandwidth and there is a risk of FCC making some of it available to unlicensed devices
2. Traffic congestion could saturate DSRC network and lead to many unsuccessful message transmission and eventually unreliable and unsafe network
3. In the rural areas, majority of intersections are not signalized and that can provide an issue with V-I communication
4. Deploying RSEs to the extent of having a fully operational DSRC network could be time consuming and costly (~$250 if the RSE can be mounted on an existing pole and up to $25k if new poles should be built[36])

With these shortcomings, DSRC is still a good candidate for localized DMA applications such as INC-ZONE and MMITSS since the do not require a widespread coverage.

10.2.2 Cellular Networks

Cellular networks, although have their own unique issues, could address some of the problems with DSRC network. Most important advantage of cellular is that there is no need to build new massive infrastructure and the already existing network of cellular towers could be utilized. Cellular systems are widely available and, driven by various consumer devices and as a result there would be a faster adoption of technology for vehicular communication purpose. Another advantage is that with the LTE and arrival of 4G and 5G technologies and their promise of better and more efficient use of bandwidth and higher throughput, the concerns of congested networks could be addressed, if a back-up cellular solution is used.

Currently, LTE communications must go through the cellular system carrier's back haul network (a network that connects the cell site to the carrier's back office systems, and generally, to the Internet) and must include an IP address. However, LTE-Direct allows communication directly between LTE terminal devices, using "Proximate Discovery" concept which lets LTE terminals to announce the services they have to offer to other terminals in the local area. This leads to one terminal providing information to other terminals in the area. Given these capabilities, an LTE-based mechanism for V2V and V2I communications could be envisioned. For any complementary system to be used, privacy (i.e. anonymity and confidentiality) and authenticity should be addressed. Moreover, security issue such as misbehavior detection should be solved.

With these limitations in place, cellular networks are a good candidate for strategic applications such as EnableATIS, FRATIS, and IDTO since they require widespread coverage and updates at a much lower frequency.

[36] AASHTO Report: National Connected Vehicle Field Infrastructure Footprint Analysis Deployment Concepts

10.3 Results Summary

As far as the suitability of RSE coverage versus cellular coverage is concerned, widespread RSE coverage is definitely beneficial for DMA applications. However, owing to the cost and the feasibility of using cellular communication for several applications, it might be cost-effective to use a hybrid approach. For example, application such as EnableATIS require wider network coverage and would require continuous RSE footprint if DSRC medium is used. However, applications such as MMITSS which require low-latency, high-resolution localized data at intersections require DSRC-based communication and hence RSE footprint around these localized areas (such as intersection approaches, incident-zones etc.)

Widespread RSE coverage is not cost-effective when applications are wide-range, such as EnableATIS. However, for applications such as MMITSS and INC-ZONE where the geographic extent is limited, RSE coverage benefits per RSE deployed might be higher.

While DSRC provides many benefits already discussed, for most V2I applications the cellular approach is feasible, and it may represent a faster adoption, lower cost, and significantly lower risk option than DSRC.

- Faster adoption is a result of the existence of hundreds of millions of smartphones already in the field, many of which could access connected vehicle services today with the simple installation of an often free application.
- Lower cost of cellular is because there is no need to build new infrastructure and the hardware and software already exists.
- Lower risk arises from the fact that the cellular user base already exists while DSRC infrastructure must be deployed and requires huge investments. The added cost of equipment in cars could be risky if the consumer does not see the additional benefit compared to what the applications on their cellphone could provide.

An optimum solution may be to have a DSRC network for V2V communication complemented by a cellular network (preferably LTE) as a backup solution to address the V2I needs.

Chapter 11. Deployment Readiness

This chapter deals with the research questions under deployment readiness category. The analysis approach includes a mix of quantitative and qualitative assessment to see whether applications are ready to be deployed in the field and how far in to the future are benefits achievable. Qualitative analysis was performed by mapping the data elements required by different prototyped applications and the data elements that are not currently in the BSM message sets. In order to assist with the quantitative assessment, the team used NHTSA's approach to map near-, mid- and long-term deployments based on a variety of factors such as deployment costs, fuel costs, fleet composition, fleet age and turnover etc. and mapped them to the market penetration used this this project. The team conducted a weighted average benefits estimation based on day-types identified by the operational conditions.

11.1 Research Questions and Hypotheses

The following research questions will be answered in this chapter.

1. To what extent are connected vehicle data beyond BSM Part 1 instrumental to realizing a near-term implementation of DMA applications? What specific vehicle data are the most critical, and under what operational conditions?
2. At what levels of market penetration of connected vehicle technology do the DMA bundles (collectively or independently) become effective?
3. What are the impacts of future deployments of the DMA bundles in the near, mid, and long term (varying market penetration, RSE deployment density, and other connected vehicle assumptions)?

In order to answer these questions, the following hypotheses have been made.

1. BSM Part 1 sent via DSRC is critical only to CACC; however other DMA applications will also need some elements of BSM Part 1 (i.e., position, speed, and acceleration) to be effective even in the near term. This is valid for all operational conditions.
2. Benefits will increase with increase in market penetration of connected vehicle technology; some bundles will yield significant benefits even at lower market penetration levels.
3. Bundles that influence traveler decision-making and leverage widely deployed mobile device technology, such as EnableATIS, FRATIS, and IDTO, will yield measureable but geographically diffused system-level impacts under near-term deployment assumptions. Bundles that influence tactical driver decision-making and depend on emerging localized low-latency messaging concepts, e.g., MMITSS, Q-WARN and SPD-HARM, will yield measureable localized benefits in urban areas under near-term deployment assumptions, but limited system-level impacts until market penetration of connected vehicle technology reaches bundle-specific thresholds.

11.2 Analysis and Research Findings

In order to answer the three research questions included in this chapter, two types of analyses are done –

qualitative analysis to find out the vehicle data that are most critical to each DMA application and what data-set they belong to; and quantitative analysis to assess the impact of connected vehicle market penetration on DMA applications.

11.2.1 Qualitative Analysis

The qualitative analysis analyzes the extent to which BSM Part 1 messages are sufficient enough to support the different DMA applications and bundles evaluated in this project. This is done by comparing the data elements required by the applications from BSM Part 1 messages and beyond. Table 11-1 shows the listing of data elements required to run individual DMA applications and their proposed sources.

Table 11-1: Data Elements Required by DMA Applications from BSM Part 1 Messages and Beyond.

Application (Bundle)	*Data Elements Required from BSM Part 1*	*Data Elements Required Beyond BSM Part 1*
Q-WARN (INFLO)	Speed and Acceleration Position (Local 3D) Queued Condition	Queued Condition
SPD-HARM (INFLO)	Current Lane Speed and Acceleration Position (local 3D)	Target Speed Target Lane
INC-ZONE (R.E.S.C.U.M.E.)	Current Lane Speed and Acceleration Position (local 3D)	Target Speed Target Lane
RESP-STG (R.E.S.C.U.M.E.)	Current Lane Speed and Acceleration Position (local 3D)	Target Lane Target Speed
MMITSS – FSP, TSP, PREEMPT	Position (local 3D) Speed and Acceleration	Vehicle Type
MMITSS – I-SIG	Position (local 3D) Speed and Acceleration	
EnableATIS	Speed and Acceleration Position (local 3D) Vehicle Size	Selected route and mode Directions and times by mode Departure location Destination Target departure time Target arrival time
FRATIS	Speed and Acceleration Position (local 3D) Vehicle Size	Freight routing with travel times Incident alerts
IDTO	Speed and Acceleration	Itinerary (destination, way points and time)

Application (Bundle)	*Data Elements Required from BSM Part 1*	*Data Elements Required Beyond BSM Part 1*
	Position (local 3D)	Passenger list Schedule status

It has to be noted that Table 11-1 shows the data element that is required by the DMA application as prototyped in the AMS project. The complete application requirements are longer and are given in Appendix B. As shown, most applications require critical data elements that are not available within BSM Part 1 messages or even BSM Part 2 messages with the exception of the currently prototyped I-SIG application in the MMITSS bundle. Therefore, alternate messaging protocols such as BMM and PDM are required for the majority of DMA applications. Chapter 7 shows an evaluation of applications and the messaging protocols require to support them.

11.2.2 Quantitative Analysis

In order to analyze the effectiveness of DMA applications under near-term, mid-term, and long-term deployments, the team used NHTSA's anticipated connected vehicle deployment rates given in Figure 11-1. These rates are defined by NHTSA by considering several different factors including application deployment, connected vehicle market penetration, and RSE deployment density. Additional factors such as communication/fuel costs, fleet composition and turn over, legal and privacy considerations as well as public acceptance. Full details on their model are provided in the report titled "Vehicle-to-Vehicle Communications: Readiness of V2V Technology for Application"[37]. Using the deployment rates from NHTSA model, the team divided the timeline from now through 2060 into three groups. Near-term is defined as before 2030, mid-term is defined as the year 2030 through 2045 and long term is defined as the year 2045 through 2060.

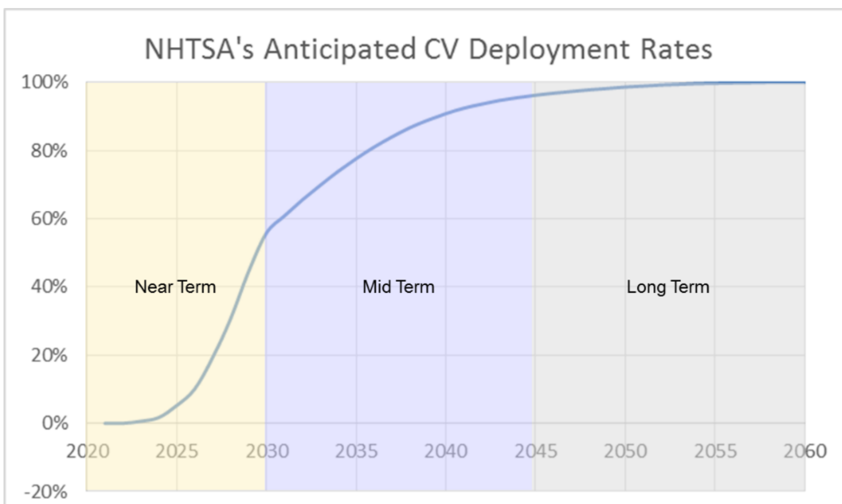


Figure 11-1: NHTSA CV Deployment Rates Mapped to Near, Mid, and Long-Term [Source: Booz Allen]

As per Figure 11-1, CV deployment up to 55 percent is achieved in near-term, 95 percent is achieved in mid-term and 100 percent achieved in long term. For this evaluation, the team used the results for different DMA applications and bundles corresponding to different market penetration and extrapolated

[37] Harding et al., NHTSA, Vehicle-to-Vehicle Communications: Readiness of V2V Technology for Application, DOT HS 812 014, August 2014.

them to a form a trending curve. The extrapolation was performed using linear regression of neighboring values and are assessed in the following subsections for SPD-HARM, Q-WARN, INC-ZONE, MMITSS, EnableATIS, and IDTO. Based on the percentage of days representing the different operational conditions, the team performed a weighted averaging of benefits based on the day-types and representative percentage of days in the data year that represented each particular operational condition. These weights are provided in Table 11-2.

Table 11-2. Percentage of Days Representing Each Operational Condition

San Mateo Testbed		Phoenix Testbed	
Operational Condition	*Percentage of Days Representing the Operational condition*	*Operational Condition*	*Percentage of Days Representing the Operational condition*
Medium Demand-High Incident (MD-HI)	13%	High Demand-Low Incident (HD-LI)	49%
Medium Demand-High Incident-Wet Weather (MD-HI-WW)	37%	High Demand-High Incident (HD-HI)	10%
Medium Demand-No Incident (MD-NI)	12%	Low Demand-Low Incident (LD-LI)	8%
High Demand-Low Incident (HD-LI)	38%	High Demand-Medium Incident-Wet Weather (HD-MI-WW)	33%

Please note that FRATIS was not assessed using different market penetration and was only evaluated using a limited prototype for three urban delivery trucks following a hypothetical delivery schedule.

SPD-HARM and Q-WARN Applications:

The performance of SPD-HARM and Q-WARN applications are assessed using the San Mateo testbed in terms of reductions in shockwaves and speed variations. The results for different deployment years are shown in Figure 11-2. As shown, the benefits increase as technology penetration increases with an initial steep ascend followed by a reduction in the rate of change of benefits. It is projected that, under the given conditions, these INFLO applications can reduce the overall shockwaves by 20 percent in the year 2030, beyond which the increase will be over the order of up to 3 percent.

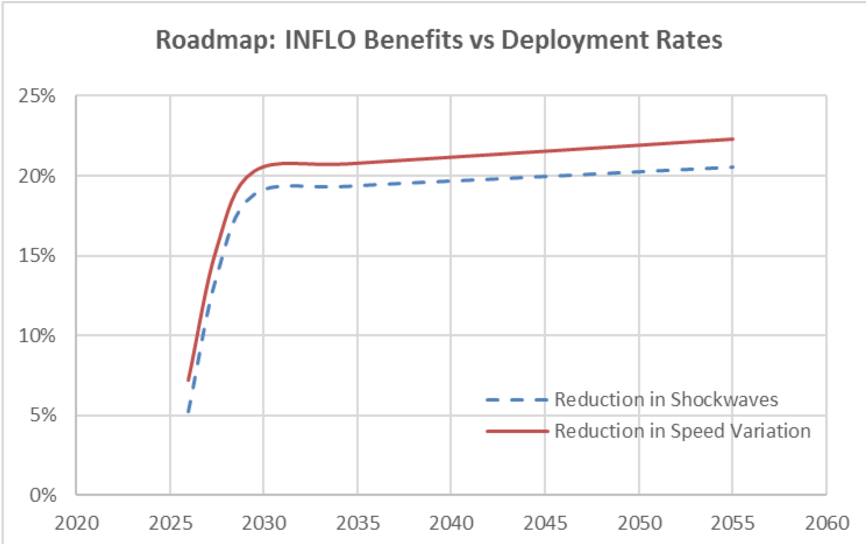


Figure 11-2: Roadmap of INFLO Benefits in Near, Mid, and Long Terms [Source: Booz Allen]

INC-ZONE Application:

Similar assessment was done in the San Mateo network using INC-ZONE application where the performance of the application is shown in Figure 11-3. Please note that this evaluation does not account to changes in crash-rates over the future years, but used the percentage benefits in the base-year to extrapolate to future years. Similar to INFLO, the INC-ZONE benefits shows an initial steep improvement and then reduces. Most of the achievement is in the near-term, with over 22 percent reduction in incident zone speed improving safety if vehicles and personnel at an incident site and increase in throughput of open lanes. There is a significant increase in the incident zone throughput as well, which is defined as the number of vehicles passing through the incident zone through the open-lanes. It was shown that, unlike incident zone speed performance measure, the throughput measure achieves benefits even in mid-term and long-term. For example, the forecasted increase in throughput increased from 15 percent in 2030 to 20 percent in 2055.

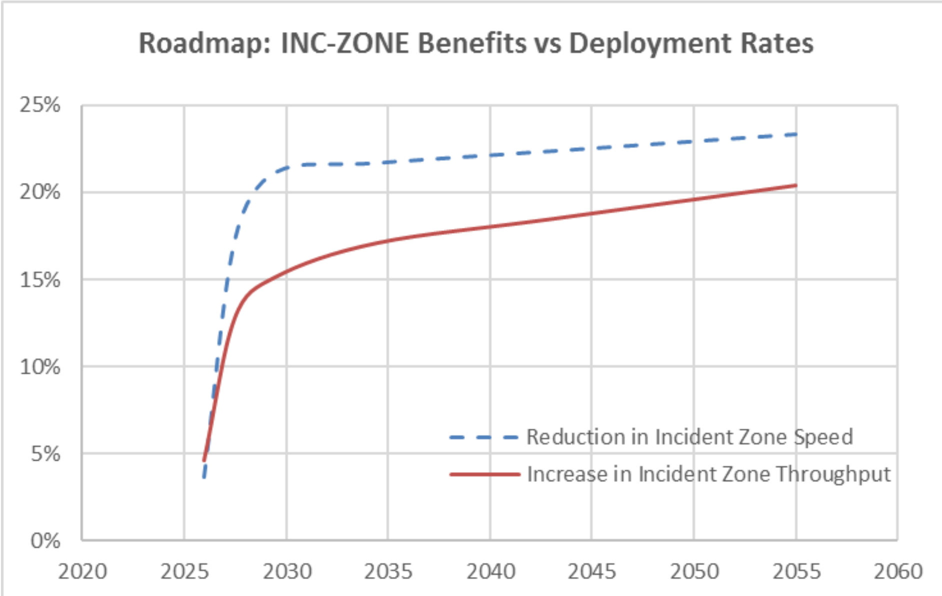


Figure 11-3: Roadmap of INC-ZONE Benefits in Near, Mid, and Long Terms [Source: Booz Allen]

MMITSS Application Bundle:

San Mateo network also assessed the MMITSS bundle, specifically the I-SIG application, to understand how deployment rates affect the benefits. Two performance measures, reduction in arterial travel time and reduction in side-street queues, were used to assess the application at 10, 25, 50, 75, and 95 percent market penetrations. As shown in Figure 11-4, the MMITSS application significantly reduces the side-street queue build-up. But this performance measure increases dramatically until mid-term deployment rate and then is stabilized. The arterial travel time decreases with a similar trend, but at a much smaller ratio than the side-street queues.

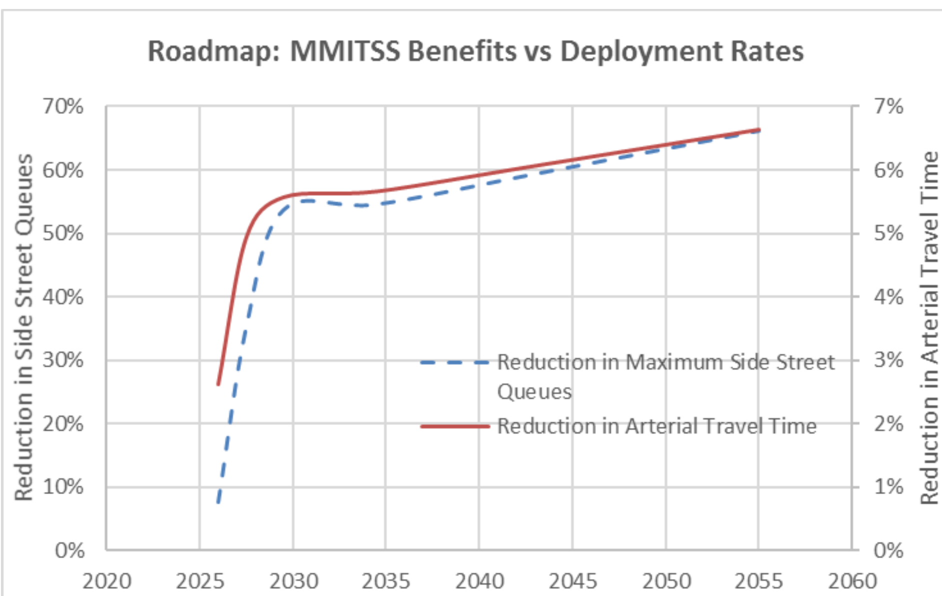


Figure 11-4: Roadmap of MMITSS Benefits of Near, Mid, and Long Term [Source: Booz Allen]

EnableATIS

EnableATIS application was assessed using the Phoenix testbed. The application aims at reducing the travel time of travelers by providing pre-trip and en-route information to drivers. The testbed team used two types of market penetration – (1) pre-trip travelers received link-specific travel times to optimize their route choice before start of the trip and maintained this route, (2) en-route travelers received link-specific travel times to optimize their routes during their trip. In order to normalize these two market penetrations to a single deployment rate, the team used the en-route market penetration as the composite market penetration rate because it is assumed that travelers with en-route information will have pre-trip as well.

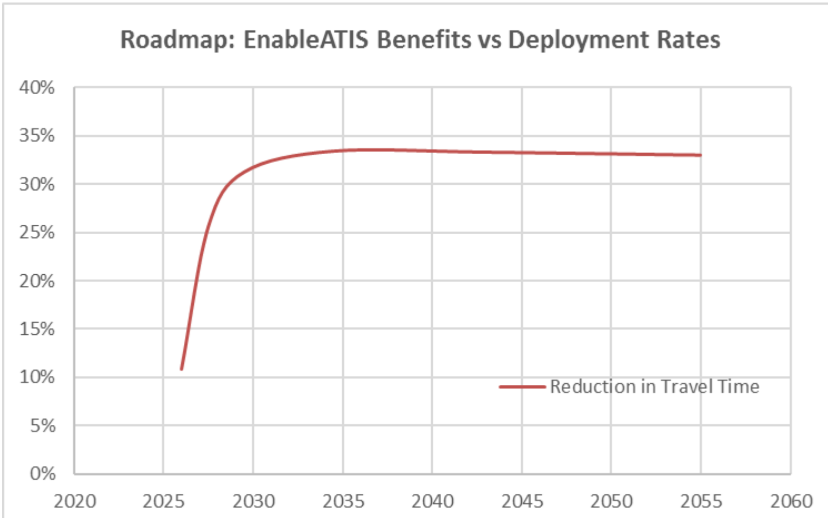


Figure 11-5: Roadmap of EnableATIS Benefits in Near, Mid, and Long Terms [Source: Booz Allen]

As shown in Figure 11-5, the travel-time reduces as deployment of connected vehicles strengthen over years. Similar to other applications, most of the benefits are achieved in near-term due to the steep deployment curve; however, there is still increase in benefits over mid-term and long-term. In near-term, the maximum reduction is around 30 percent, whereas in mid-term and long-term, this increases to 40 percent and 45 percent respectively.

IDTO

The Phoenix testbed was also used in analyzing the IDTO bundle. T-DISP application was used to inform transit travelers on the best possible transit lines to utilize to reduce the travel time for transit passengers. Three different market penetration were used (20 percent, 50 percent, and 80 percent) to assess the reduction in travel time due to the application. A mapping of these benefits for different deployment rates are shown in Figure 11-6. As shown, there is up to 8 percent reduction in transit travel time in near term, 11 percent reduction in mid-term and 12 percent reduction in long-term due to T-DISP application. D-RIDE application was not assessed using different market penetration since it was developed as a limited prototype. Please note that these benefits indicate extrapolation of current benefits of T-DISP. As technology and transit services advance, there might be additional benefits. In addition, the team used an average of a sample short-, medium-, and long- origin and destination pairs in this assessment and extrapolated them for average transit demand in the Phoenix region.

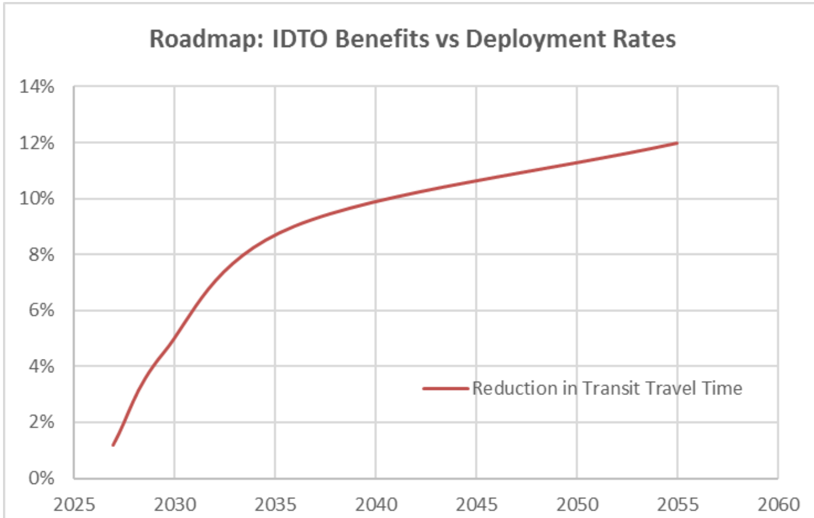


Figure 11-6: Roadmap of IDTO Benefits in Near, Mid, and Long Terms [Source: Booz Allen]

11.3 Results Summary

As shown in the previous subsection, the performance of applications and bundles improve as more and more vehicles get equipped. For this assessment, the team used a combination of qualitative and quantitative assessment to see whether applications are ready to be deployed in the field and how far in to the future are benefits achievable. Qualitative analysis was performed by mapping the data elements required by different prototyped applications and the data elements that are not currently in the BSM message sets. In order to assist with the quantitative assessment, the team used NHTSA's approach to map near-, mid- and long-term deployments based on a variety of factors such as deployment costs, fuel costs, fleet composition, fleet age and turnover etc. and mapped them to the market penetration used this this project.

Individual DMA applications showed maximum increase in benefits under near-term, when the CV market penetration is between 40 to 60 percent, beyond which the rate of increase in benefits slows down.

Qualitative assessment showed that most of the DMA applications, with the exception of Individual DMA applications require connected vehicle data elements beyond BSM for its functioning. The quantitative assessment showed maximum increase in benefits under near-term, when the CV market penetration is between 40 to 60 percent, beyond which the rate of increase in benefits slows down.

Chapter 12. Analysis of Deployment Costs and Benefits

This chapter analyzes the deployment costs for deploying DMA applications as well as the benefits from these deployments. These analyses were conducted using cost- and benefit- estimation models developed by the DMA Program Evaluation team for National-Level Impacts and Cost Estimation[38]. Booz Allen team adapted the national-level model to the testbeds that were evaluated, namely, San Mateo and Phoenix. As per recommendation from the DMA Program Evaluation team, the Booz Allen team did not combine the deployment costs with benefits model, since the deployment costs are not primarily associated with deploying DMA applications, but with the CV technology. The deployment costs and benefits are closely tied to the testbed used for analysis owing to the size, deployment characteristics and assumptions as well as the impacts demonstrated through modeling in the previous chapters. Please note that the deployment and benefit estimation models utilized in this chapter are not comprehensive and can only be used as an indicative of the actual benefit/cost estimation process owing to the large number of unknowns. The next section explains some of the major assumptions that are used in the models and readers are encouraged to read additional assumptions in FHWA-JPO-16-419 report.

12.1 Model Assumptions

Figure 12-1 shows the adapted model that was developed by the Booz Allen team to conduct DMA Applications' impact and cost estimation.

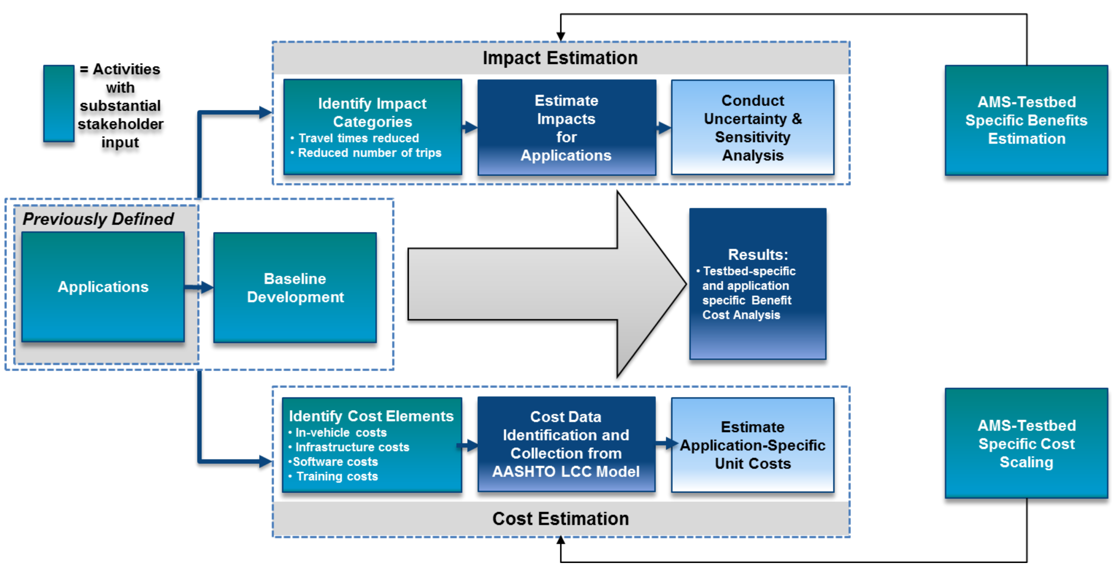


Figure 12-1: Cost and Impact Estimation Models Adapted to AMS Project [Source: Booz Allen]

38 Cordahi et al., Dynamic Mobility Applications Program Evaluation: National-Level Impacts and Costs Estimation Report, FHWA-JPO-16-419.

As shown, the models were built on baseline estimations for both cost and impact estimation. This include elements such as roadway lengths, facility types, transit types, emergency vehicle stations, VMT, crash rates etc. in San Mateo and Phoenix regions. The impact estimation was done using the impact categories identified by the DMA team, which in most cases, was travel time. All other performance measures were converted to travel time savings so that affecting value of time computation could be made. Therefore, specific safety-based as well as reliability-based performance measures were not used for this analysis. Cost estimation models were developed based on the cost categories identified by AASHTO and USDOT's CO-PILOT tool. Readers are encouraged to refer to the DMA Program Evaluation report for detailed analysis methodology.

As with any benefit-cost assessment model, several assumptions were made by the DMA team and Booz Allen team in conducting this analysis. These are provided below:

- DMA deployment rate used follows the least aggressive NHTSA scenario for safety applications deployment. These curves and details of estimation are provided in Chapter 11. The RSU deployment rates are also assumed the same as the OBU deployment rates provided by NHTSA.
- Benefits assessment rely on direct volume drivers that are mobility-based, such as travel-time. Impact of safety-based and reliability-based performance measures are not included in this study.
- Vehicle miles traveled only considers number of vehicles traversing the testbed annually.
- Analysis period considered spans from the year 2021 to 2060 (40 years).
- The AASHTO Life Cycle Cost (LCC) model was used as the basis for the DMA cost estimation cost model.
- The compliance rate and adoption rate are assumed to be accounted for in the deployment rate percentages. For example, when 25 percent deployment is achieved, it means that the 25 percent is a representative number depicting the number of users that are equipped and make use of the technology.
- Each of the cost elements considered in this analysis is categorized as infrastructure, in-vehicle, software, or training costs. A listing of these cost elements is provided in Table 5-2.
- Unit costs, O&M costs, and expected useful life data for each element is collected from the AASHTO LCC model.
- The deployment costs were computed assuming that the elements won't be shared by applications. In real-life, the costs will be shared between applications as more applications get deployed.
- Results are expressed in 2012 dollars.
- The estimated VMT annual growth rate is 2.4 percent.
- Growth in hourly wages is used to estimate the Value of Time (VoT), which is used to monetize the impacts of the DMA applications. The annual growth rate for the hourly wages forecast is 2.57 percent.
- Incident rates use a decline rate of 2.05 percent.
- The compound annual growth rate (CAGR) for the total ridership on all transit modes is 1.133 percent.
- Cost estimation analysis only considers costs incurred by the government.
- The compound annual growth rate (CAGR) for the total ridership on all transit modes was 1.133 percent.
- The annual decline rate for incidents on freeway is -2.05 percent.
- Number of ambulance per station is 2.5 with 3 drivers assigned to each vehicle.
- Freeways are assumed to be 0.5 miles per segment.
- Transit trips for City of Tempe are 4 percent of the greater Phoenix area.

12.2 Deployment Costs

Since the Booz Allen team used the DMA Program Evaluation model[39], only applications that are covered in that model is analyzed for year-wise deployment costs in this project. This includes Q-WARN and SPD-HARM applications from INFLO bundle, I-SIG from MMITSS bundle, INC-ZONE from R.E.S.C.U.M.E. bundle, T-DISP from IDTO bundle and the FRATIS application. As mentioned earlier, the team used the model that was developed by DMA Program Evaluation team for National-level Impact Assessment for this analysis by scaling down the model to regional levels. Four types of costs were included in the deployment costs, including in-vehicle costs, training costs, infrastructure costs, and software development and implementation costs. A list of these cost elements by application is provided in Table 5-2. These elements, corresponding to each application is provided in the following list, along with the corresponding volume drivers.

1. Transit Vehicles:
    a. Training costs estimated per driver.
    b. Transit retrofit kits are estimated per transit vehicle.
    c. Transit retrofit kit software package costs per transit vehicles.
    d. Mobile (cellular-based) carry-in device including cellular data plan per transit user.
2. Public Safety Vehicles:
    a. On-board Unit estimated per vehicle.
    b. Software packages to supplement OBUs are also estimated per vehicle.
    c. Driver training costs are estimated per trained operator.
3. Signalized Intersections:
    a. Backhaul communications upgrade estimated per intersection in the region.
    b. Inductive loop detectors estimated per intersection
    c. Roadside Equipment (RSEs) will require to be deployed per intersection.
    d. Signal Controllers upgrade is estimated per intersection
    e. RSE Planning and Design costs are also estimated per intersection.
    f. Pucks (sub-surface temperature sensors) and other Road Weather Information Systems (RWIS) are also estimated per intersection.
4. Commercial Trucks
    a. Truck Retrofit Kit, representing On-Board Units are estimated per truck.
    b. Truck OBU Software package estimated per truck.
    c. Mobile (cellular-based) carry-in device (estimated per truck) including cellular data plan.
    d. Driver training costs are estimated per driver.
5. Freeway Segments
    a. Backhaul communications upgrade is estimated at a 0.5-mile length freeway.
    b. Inductive loop detectors placed at 0.5-mile interval on a freeway.
    c. Roadside Equipment (RSEs) placed at 0.5-mile interval on a freeway to support ubiquitous coverage.
    d. RSE planning and design also computed at 0.5-mile segments of freeway
    e. Pucks and other Road Weather Information System (RWIS) sensors placed at 0.5-mile freeway segments,
    f. CCTV Camera placed at 0.5-mile freeway segments.

The following subsections demonstrate the deployment costs for the San Mateo and Phoenix regions.

[39] Cordahi et al., Dynamic Mobility Applications Program Evaluation: National-Level Impacts and Costs Estimation Report, FHWA-JPO-16-419.

12.2.1 San Mateo Testbed Region

As far as deployment costs are concerned, the team performed cost-analysis on INFLO, INC-ZONE and MMITSS's I-SIG application. While Q-WARN and SPD-HARM are prototyped together, their deployment costs assume separate deployment costs for either of them, based on the DMA Program Evaluation model. Figure 12-2 below show the deployment costs for Q-WARN application as annual costs and deployment costs. The costs are also tagged alongside the application deployment curves. As indicated, the infrastructure costs take up almost 50 percent of the total cumulative costs of approximately $4,600,000 (in 2012 dollars).

Figure 12-3 below show the deployment costs for SPD-HARM application. The final cumulative cost incurred by year 2060 expressed in year 2012-dollar amount is around $4,200,000. There are several shared components between Q-WARN and SPD-HARM applications and deploying them together would not cost the sum of two deployments. Additional modifications to the model are necessary for this analysis and are therefore not covered in this report. A listing of these shared cost elements is provided in Table 5-2 for reference. Please note that there are multiple peaks in the annual costs. Due to the steep slope of deployment curve during the first 10 years of deployment, the majority of in-vehicle equipment and software's costs are incurred in the first few years. This is the reason for the first peak in the graph. This large amount of in-vehicle equipment and software have a 7-10-year refresh/upgrade cycle based on the CO-PILOT model. The second peak is showing this end of useful life upgrade cost. This cycle continues for the following years. However, due to the scale of the graph and the much lower deployment rate in the later years, the refresh cycles are not noticeable.

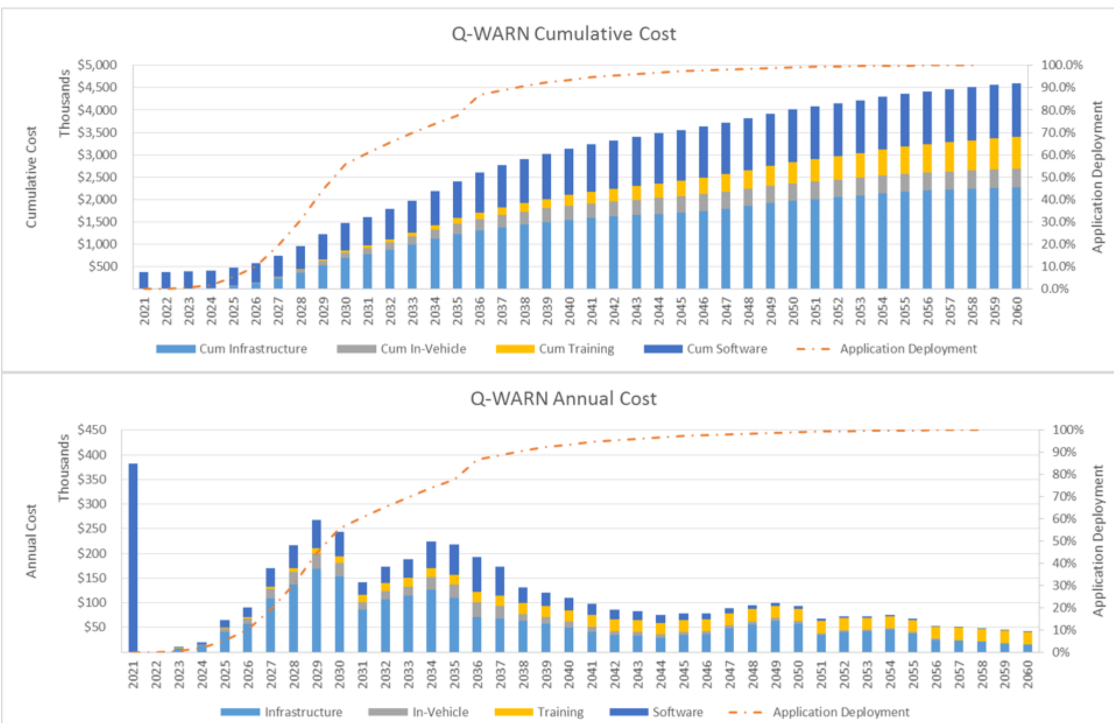


Figure 12-2: Deployment Costs for Queue Warning Application in San Mateo Region [Source: Booz Allen]

Similar analysis was performed for Intelligent Signal Control application. For I-SIG, the final cumulative cost incurred by year 2060 expressed in year 2012-dollar amount is approximately $4,300,000 as shown in Figure 12-4. Unlike INFLO applications, only a third of the overall deployment costs for I-SIG are for infrastructure. The training costs and software costs also count towards a major share of the deployment costs.

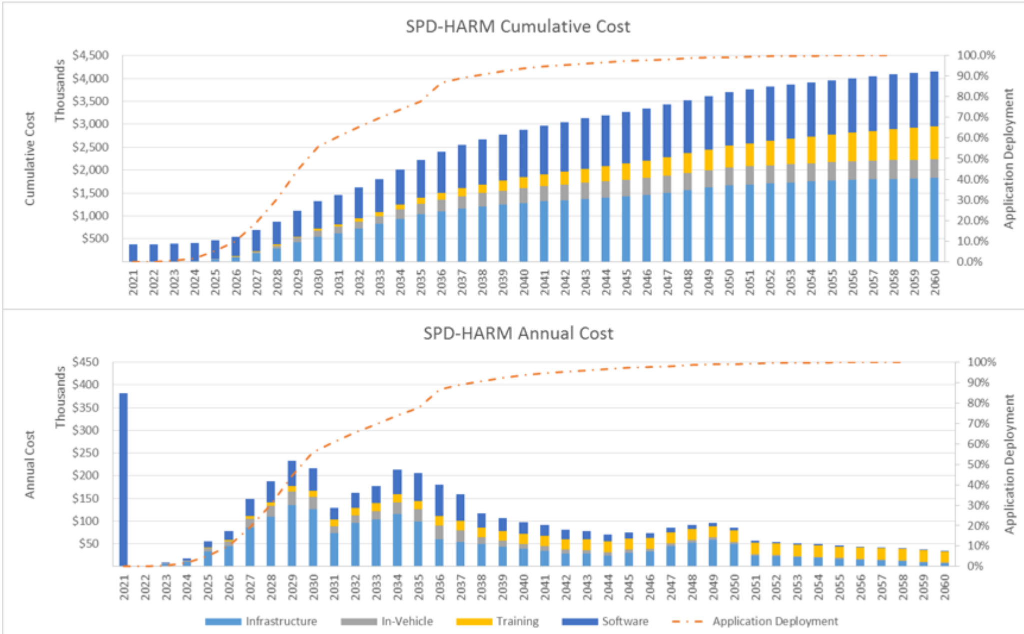


Figure 12-3: Deployment Costs for Speed Harmonization in San Mateo [Source: Booz Allen]

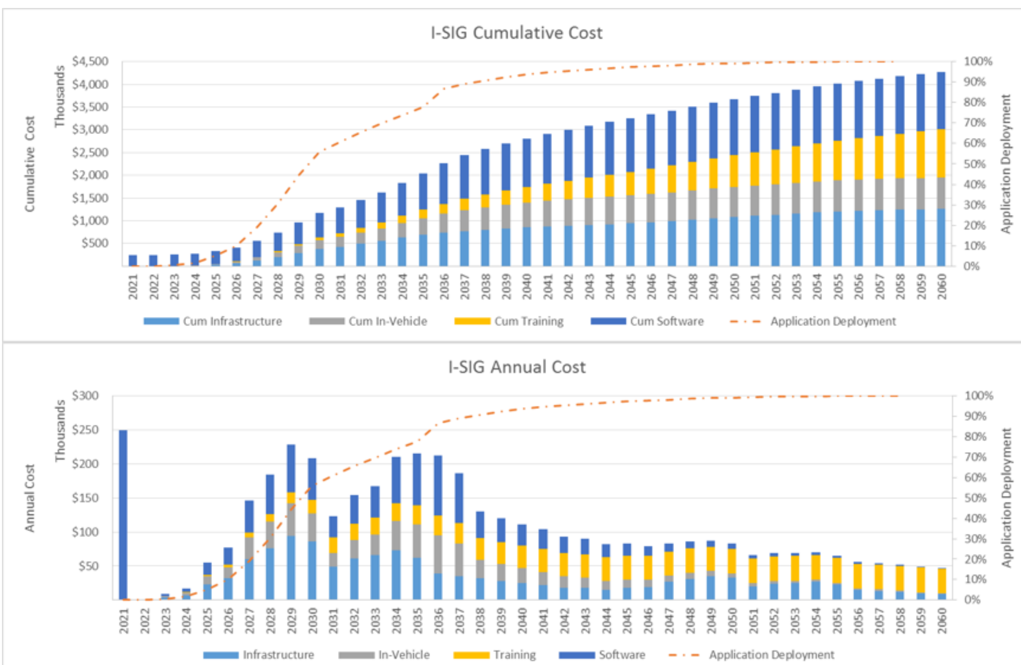


Figure 12-4: Deployment Costs for Intelligent Signal Control in San Mateo [Source: Booz Allen]

Figure 12-5 below show the deployment costs for INC-ZONE application. The final cumulative cost incurred by year 2060 expressed in year 2012-dollar amount is $3,500,000. As shown, only 10 percent of the total cost is for infrastructure elements. Software accounts to the highest cost element with almost 35 percent of the cumulative costs.

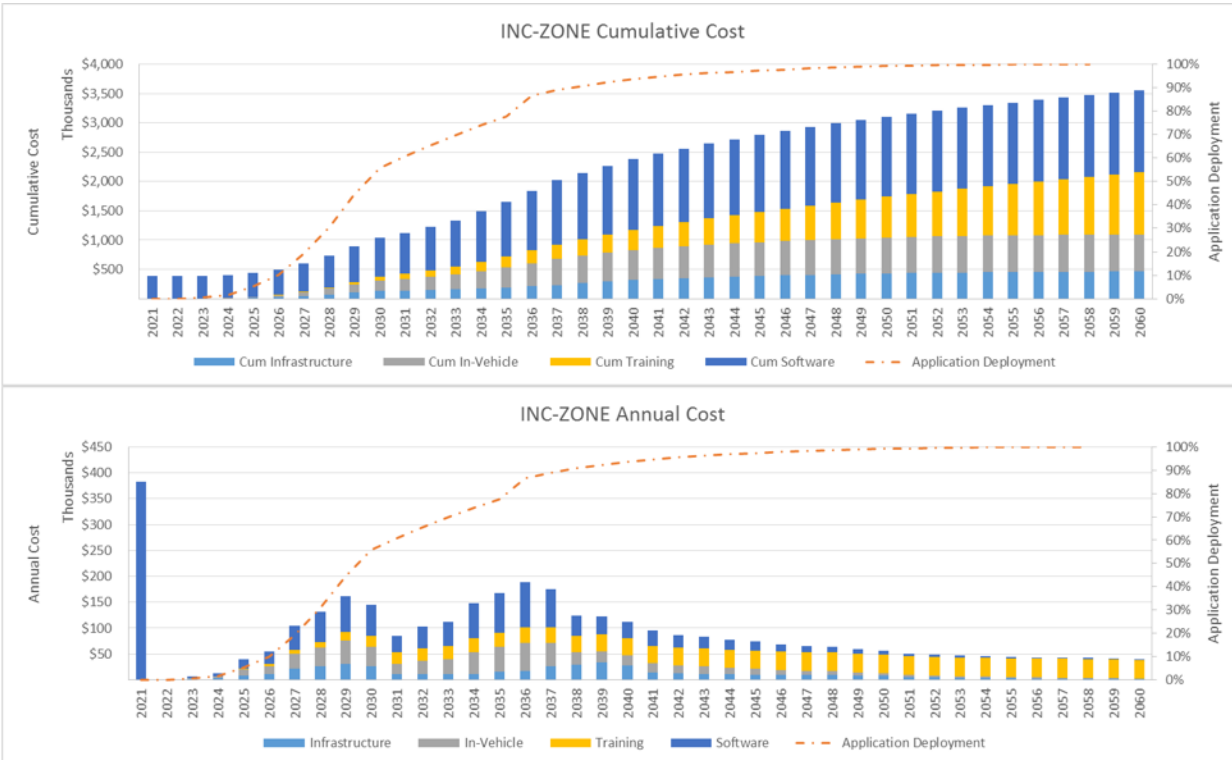


Figure 12-5: Deployment Costs for Incident Zone Application in San Mateo [Source: Booz Allen]

12.2.2 Phoenix Testbed Region

The Phoenix testbed is used to evaluate the three strategic applications – EnableATIS, FRATIS, and IDTO. The DMA Program Evaluation models do not evaluate EnableATIS costs since it is envisioned to be an application utilized by the road-users using the available CV and legacy system data. Figure 12-6 below show the deployment costs for FRATIS bundle. The final cumulative cost incurred by year 2060 expressed in year 2012-dollar amount is $10,000,000 with more than half of the costs due to expensive software systems used by FRATIS.

Figure 12-7 below shows the deployment costs for T-DISP application of the IDTO bundle. D-RIDE application was not analyzed for deployment costs by the DMA evaluation team. The final cumulative cost incurred by year 2060 expressed in year 2012-dollar amount is $2,000,000. Almost 80 percent of the expense for IDTO is for infrastructure costs.

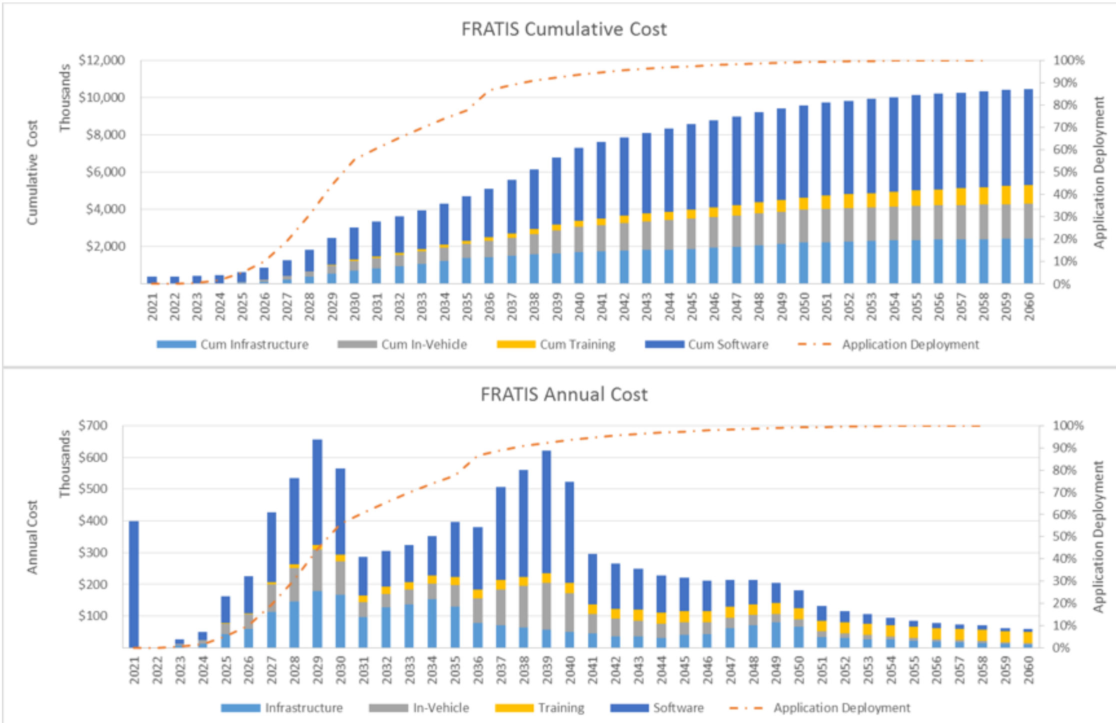


Figure 12-6: Deployment Costs for FRATIS Application in Phoenix Region [Source: Booz Allen]

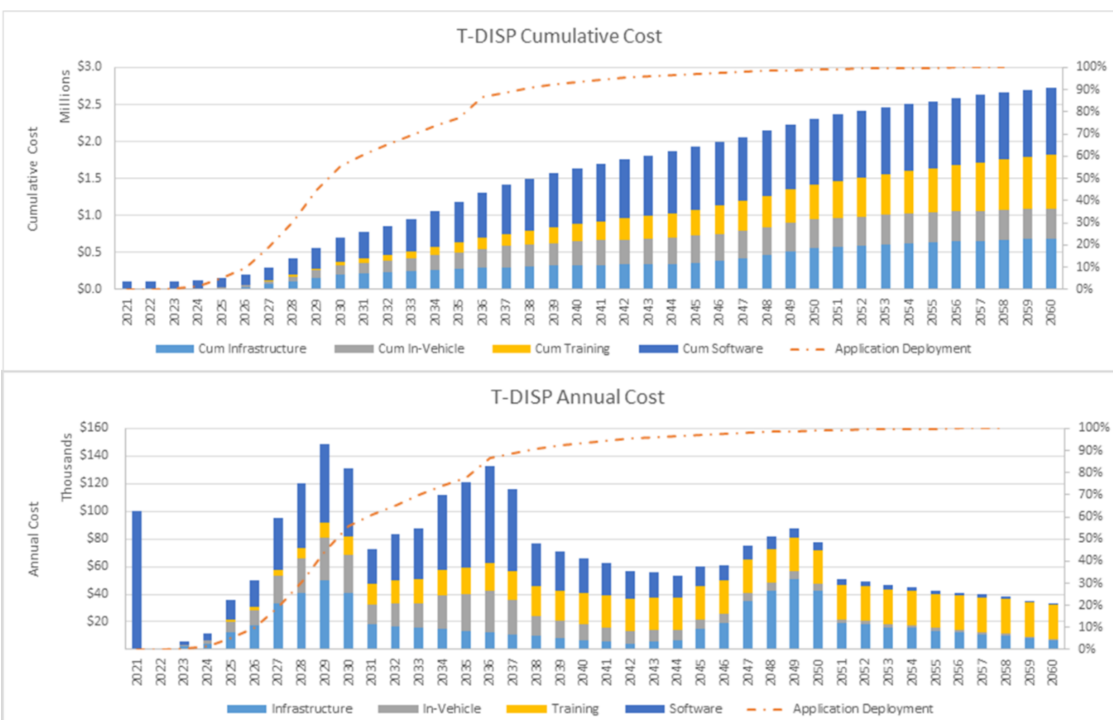


Figure 12-7: Deployment Costs for T-DISP Application (IDTO Bundle) in Phoenix Region [Source: Booz Allen]

12.3 Benefits Analysis

Booz Allen team evaluated the benefits from different applications using volume drivers defined by the DMA Evaluation model[40], travel time savings. The travel time savings was normalized per VMT using the national model and was adapted to San Mateo and Phoenix regions for different applications based on the benefits given by the applications. Only applications that provide travel time savings are assessed in this project. Other performance measures were not translated to travel time savings due to the complexity in application behavior. For example, SPD-HARM does not provide any travel time savings, but reduces the shockwaves on the freeway. Savings from increased travel time reliability through reduction in unexpected delays were also not accounted for in the DMA Evaluation model. These benefits were not evaluated as dollar values in this model. Please note that only mobility-based benefits were used in this model although some of the DMA applications are envisioned to have greater safety benefits than mobility benefits. The DMA Evaluation model assumes the implementation costs for each application bundle as independent with no existing CV technology infrastructure already existing. In reality the cost will be shared between application bundles.

12.3.1 San Mateo Testbed Region

Only MMITSS I-SIG application benefits were used in the analysis of value of time saved, since INFLO did not impact the total travel time. Additionally, INC-ZONE application was tied to the type of crashes and could not be normalized without actual crash-rates. Figure 12-8 below show the travel time benefits in dollar value for MMITSS bundle. The final cumulative benefits gained by year 2060 expressed in year 2012-dollar amount is $6,200,000.

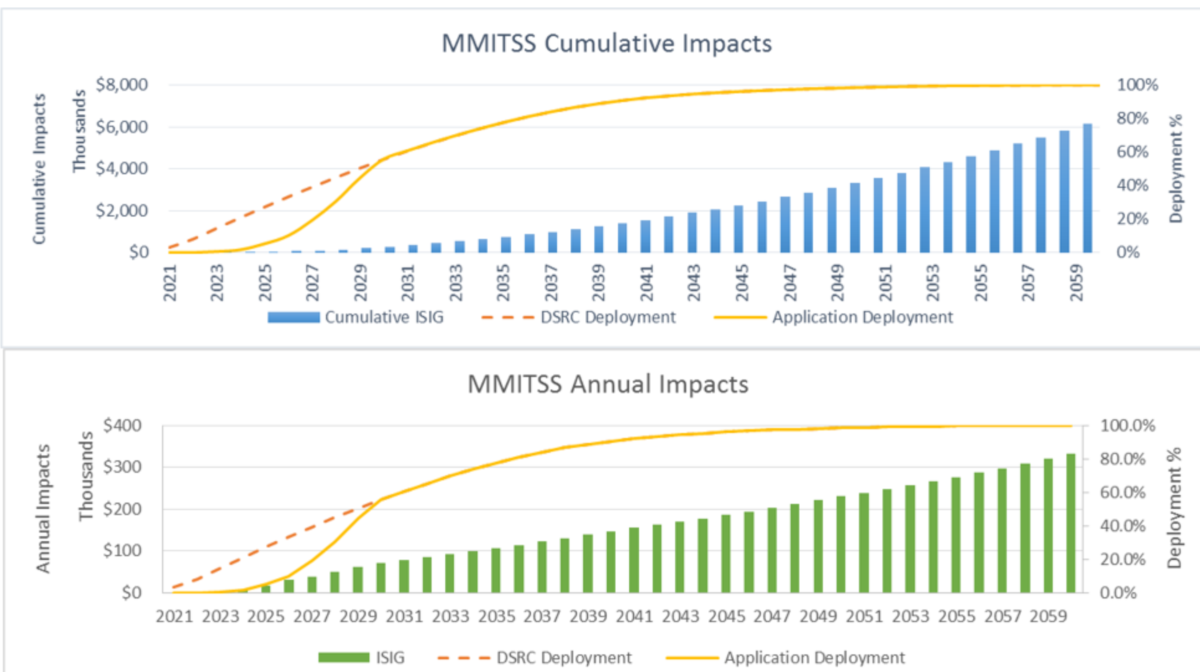


Figure 12-8: Value of Benefits from MMITSS I-SIG Application in San Mateo Region [Source: Booz Allen]

[40] Cordahi et al., Dynamic Mobility Applications Program Evaluation: National-Level Impacts and Costs Estimation Report, FHWA-JPO-16-419.

12.3.2 Phoenix Testbed Region

The two applications assessed under Phoenix region are FRATIS and T-DISP. Figure 12-9 below show the travel time benefits in dollar value for FRATIS bundle. The final cumulative benefits gained by year 2060 expressed in year 2012-dollar amount is around $1,000,000. Figure 12-10 below show the travel time benefits in dollar value for T-DISP application. The final cumulative benefits gained by year 2060 expressed in year 2012-dollar amount is $1,100,000.

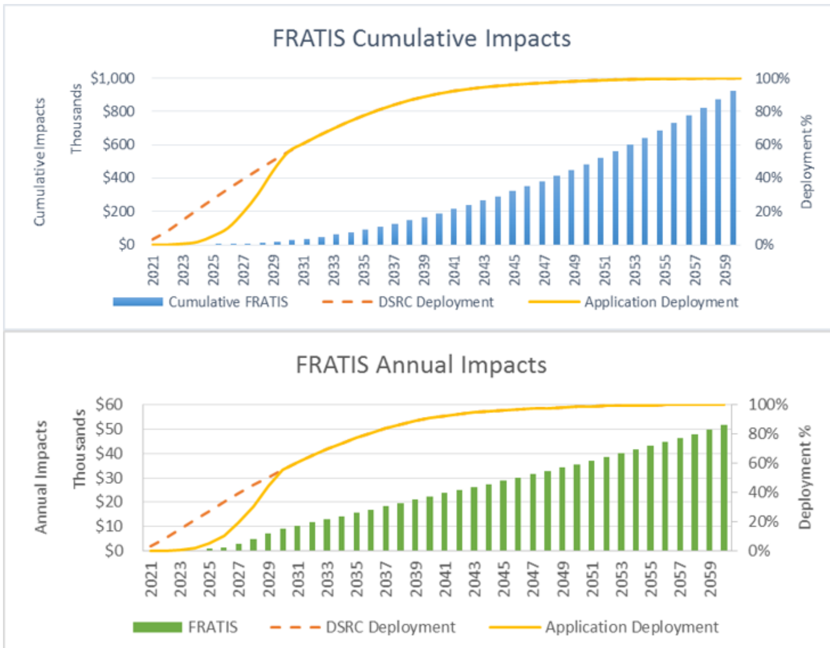


Figure 12-9: Value of Benefits from FRATIS Application on Phoenix Region [Source: Booz Allen]

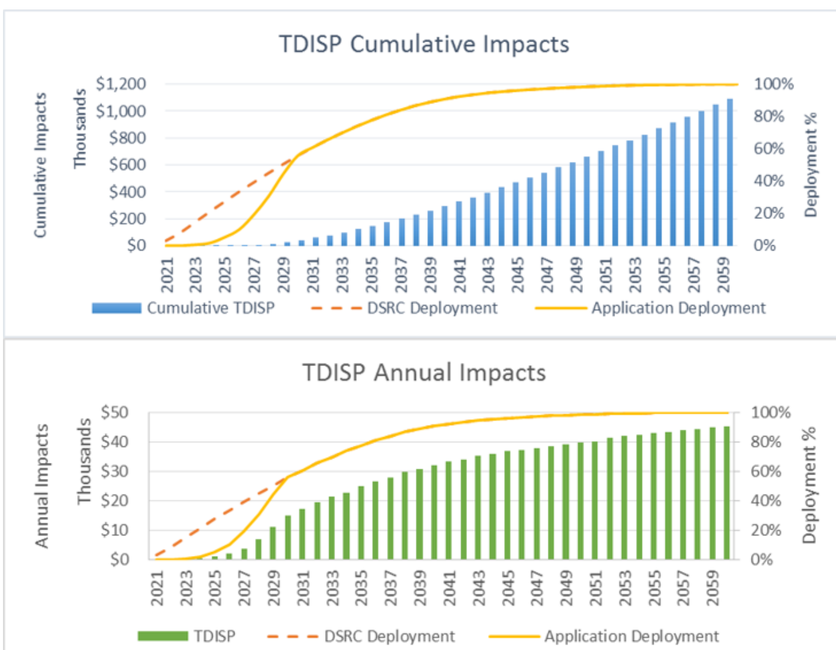


Figure 12-10: Value of Benefits from T-DISP Application on Phoenix Region [Source: Booz Allen]

12.4 Summary of Results

This chapter analyzed the costs and benefits associated with each DMA application/bundle on San Mateo and Phoenix region using a cost-benefit model developed by the DMA Program Evaluation team for National-Level Impact Estimation. As shown in this chapter, benefits and costs from this model cannot be used in a trade-off analysis, since costs developed does not account for shared costs as well as costs for deployment of DMA applications as a supplement to other applications. In addition, the costs used in this model are from the CO-PILOT tool which is only meant for high-level estimation for pilot projects and not for full-fledged deployments. However, under lack of other sources and specific assumptions made, the team evaluated the deployment costs and value of benefits from individual applications by adapting a national level model to a regional scale. Table 12-1 provides a summary of deployment costs and value of benefits associated with applications

Table 12-1: Summary of Deployment Costs and Value of Benefits

Testbed	***Application***	***Deployment Costs****	***Value of Benefits***
		(in Millions of 2012 Dollars)	
San Mateo	Q-WARN	4.6	
	SPD-HARM	4.2	
	I-SIG	4.3	6.2
	INC-ZONE	3.5	
Phoenix	FRATIS	10	1
	T-DISP	2	1.1

*Deployment Costs are assessed when implemented as non-shared deployment.

Chapter 13. Summary of Results

This report evaluates DMA applications and bundles for specific elements with respect to data, synergies and conflicts, connected vehicle protocols, and communication attributes. This chapter summarizes the major findings made in this research and is categorized according to the different research question types.

13.1 Connected Vehicles and Legacy Systems

This analysis used simulations with different data inputs to the applications to assess whether DMA applications will yield benefits when legacy system data is supplemented or replaced with connected vehicles Data. The results were application-specific. For INFLO and MMITSS, legacy system data is contributing to most benefits at lower market penetration and CV data at higher market penetration. Applications such as FRATIS and INC-ZONE require CV data to work and hence were not evaluated for effectiveness under different data sources. EnableATIS application relied mostly on legacy data and addition of CV data caused marginal improvement in benefits.

The results indicate that at lower CV market penetration, DMA applications such as INFLO and MMITSS rely mostly on data from legacy systems to provide mobility benefits. However, as market penetration increases, this reliance can be replaced. For example, at 10 percent market penetration, the connected vehicle data only provided marginal reduction in shockwaves due to INFLO application, whereas data from legacy systems provided up to 21 percent reduction in shockwaves. But, at 50 percent market penetration, the reduction in shockwaves due to INFLO subscribing to CV data improved to up to 23 percent. Compared to legacy systems, DMA applications that make use of new forms of wirelessly-connected vehicle, infrastructure, and mobile device data will yield cost-effective gains in system efficiency and individual mobility, when at least 25 percent of vehicles can wirelessly communicate with the DMA applications. Similar trend was shown by MMITSS application. It was demonstrated that higher reductions in arterial travel time occurred when the application supplemented CV data with Detector data than the CV data alone. Additionally, it was shown that MMITSS application could work without legacy system data (detector calls), when the market penetration is higher.

EnableATIS applications also demonstrated greater benefits when legacy data was supplemented with CV data in terms of reduction in travel time. However, this improvement was marginal and legacy data contributed to most benefits.

13.2 Synergies and Conflicts

In order to assess the impact of combination of applications, MMITSS, INC-ZONE and INFLO were assessed in isolation and in combination. It was found that these applications are synergistic in nature, with combination of applications showing better performance measures than isolation, but at higher market penetration of connected vehicle technology.

INFLO and INC-ZONE applications, both being freeway-based applications, were assessed in isolation and combination for reduction in shockwaves (INFLO-specific performance measure) and increase in effective throughput (INC-ZONE specific performance measure). At market penetrations about 10 percent, these applications performed better in combination. For example, at 50 percent market penetration, the average reduction in shockwaves increased from 13 percent to 15 percent when INFLO was combined with INC-ZONE. The average increase in the throughput of open lanes in an incident zone increased from 50 percent to 58 percent when INC-ZONE was combined with INFLO.

INFLO and MMITSS applications were assessed for improvement in overall network delay in isolation and in combination. At any market penetration, the combination was shown to be better than isolated applications. For example, at 50 percent market penetration, the reduction in overall delay in the network increased from -1 percent (INFLO only) and 3 percent (MMITSS only) to almost 11 percent when the applications were combined. Therefore, the applications are synergistic. Similar trend was also shown for the INC-ZONE and MMITSS application combination where the reduction average network delay increased from 2 percent to almost 5 percent. Please note that these assessments were done on specific operational conditions.

The team also evaluated the combinations of tactical group of applications with strategic group of applications using qualitative research which looks into the specific network entity that is controlled by each application. No primary conflict or synergy was found since these groups of applications impact different aspects of the network. For example, applications such as EnableATIS, FRATIS, and IDTO impact the mode/route choice of the travelers whereas applications such as INFLO, INC-ZONE, and MMITSS impact the driver behavioral parameters such as speed and lane selection.

Operational Conditions Modes and Facility Types

The benefits from DMA applications are dependent on the operational conditions in terms of demand in the system, weather conditions, and induced incidents. In this chapter, we assessed INFLO, INC-ZONE and MMITSS applications, in isolation and in combination under different operational conditions. In addition, EnableATIS, FRATIS, and IDTO applications were assessed using the Phoenix testbed. A summary of the results in terms of different operational conditions that yield maximum benefits to specific application/combination is provided below. It shows the mapping of applications and their preferred facility types. The facility types have been identified based on the application’s functionality and design.

Applications/Combinations and their preferred operational conditions

Application/ Combination	*Operational Conditions that Yield Maximum Benefits*
INC-ZONE	Medium demand and high incident severity yield maximum throughput for open lanes and high demand and low incident severity yield safer (maximum reduction in) speeds for vehicles in incident zones.
INFLO	Medium Demand/No Incident operational conditions yield maximum benefits in terms of reduction in shockwaves and speed variations.
MMITSS	Medium Demand/No Incident operational conditions yield maximum benefits in terms of reduction in side-street queues, and medium demand with high incident severity yield maximum benefits in terms of arterial travel time.

Application/ Combination	Operational Conditions that Yield Maximum Benefits
EnableATIS	High demand, medium incident severity, and wet weather operational conditions provided maximum benefits in terms of travel time saved.
FRATIS	High demand and high incident severity provided maximum benefits in terms of truck travel time.
IDTO	Low demand and low incident severity provided maximum benefits in terms of travel time saved for transit passengers.
INFLO+INC-ZONE	High demand and low incident severity provided maximum benefits in terms of two of the safety-based performance measures, namely reduction in shockwaves and reduction in speeds at the incident locations.
INC-ZONE+MMITSS	Medium demand and high incident severity provided maximum benefits in terms of average network speed and delay.
INFLO+MMITSS	Medium demand and high incident severity provided maximum benefits in terms of average network speed and delay.

13.3 Messaging Protocols

The team mapped different messaging protocols, such as BSM, BMM, and PDM etc. to support different applications to assist in a qualitative assessment of which messaging protocols are optimal to each application. The mapping was based on the input requirement for each of the modeled application. Applications such as INFLO (SPD-HARM and Q-WARN) and INC-ZONE require messaging at a much longer frequency than 10Hz since they act on a wider area. For example, SPD-HARM application acts along a freeway corridor and CV data is only used to identify harmonized speeds over sections of freeway at a minimum resolution of 5 miles per hour with an update frequency of 20 seconds. Therefore, messages such as BMM or PDM can be used in lieu of BSM messages. The MMITSS application, however, is much more localized. From the application design, it is evident that the BSM messages are instantly used to place advanced calls to the detector phases and it is imperative that these messages are delivered at lowest latency and fastest frequency. Therefore, BSM messages are critical for this application. Our hypothesis that only some application would require messaging at 10Hz frequency is therefore true.

Criticality of en-route or pre-trip messaging was assessed using EnableATIS through simulations that represented different market penetration of VMS equipage, en-route, and pre-trip route optimization. The results indicate that the en-route messaging is important in leveraging all of the benefits of the application. With just pre-trip messaging, travelers may not have access to the most optimum routes based on changing traffic conditions. Pre-trip and en-route messaging also indicated higher travel distance, but the travel time was always lower than the baseline.

13.4 Communication Technology

For localized and safety-critical applications, low-latency communication with neighboring devices is critical; this favors direct V2V communication through a simple medium access control protocol. DSRC (approximately 200 microsecond) would certainly fare better compared to LTE (below 5 millisecond). However, the DMA bundle applications are focused on mobility and could afford higher latency mediums. Moreover, with comparatively better latency of 4G and promise of 5G, latency issue of cellular could be easily addressed. Given that the rate of communication update required for most DMA applications is more than 0.1 second, both DSRC and cellular could satisfy the requirement and latency risk could be minimized.

From our analysis, a nomadic device capable of communicating via DSRC and cellular will be very useful for DMA applications. Certain applications/bundles that require localized deployment works best using DSRC, whereas others prefer cellular (e.g. CACC). Most DMA applications, with the exception of CACC, do not rely on the low-latency characteristic of DSRC since they can afford to have a sub-second latency.

13.5 Communication Latency

Communication latency and losses significantly affect the performance of applications. This chapter assessed the impact of these communication attributes on INFLO's speed harmonization and queue warning, R.E.S.C.U.M.E.'s incident zone alerts application and the MMITSS bundle. INFLO was assessed for reduction in shockwaves and speed variations and showed that latency values beyond 3 seconds deteriorated the application performance by more than 50 percent, whereas losses beyond 10 percent virtually had zero benefits on shockwave reduction. INC-ZONE application's assessment showed that it is more sensitive to latency with almost 60 percent benefits being lost with 1-second latency. MMITSS had the highest impact due to communication latency, since it had a higher update frequency when compared to INFLO and INC-ZONE. Even a 0.5-second latency deteriorated MMITSS's benefits by over 90 percent and higher latencies caused disbenefits to the system. The impact of communication losses in INC-ZONE and INFLO were similar to reduction in market penetration.

13.6 RSE/DSRC Footprint

As far as the suitability of RSE coverage versus cellular coverage is concerned, widespread RSE coverage is definitely beneficial for DMA applications. However, owing to the cost and the feasibility of using cellular communication for several applications, it might be cost-effective to use a hybrid approach. For example, application such as EnableATIS require wider network coverage and would require continuous RSE footprint if DSRC medium is used. However, applications such as MMITSS which require low-latency, high-resolution localized data at intersections require DSRC-based communication and hence RSE footprint around these localized areas (such as intersection approaches, incident-zones etc.)

While DSRC provides many benefits already discussed, for most V2I applications the cellular approach is feasible, and it may represent a faster adoption, lower cost, and significantly lower risk option than DSRC.

- Faster adoption is a result of the existence of hundreds of millions of smartphones already in the field, many of which could access connected vehicle services today with the simple installation of an often free application.
- Lower cost of cellular is a result of not needing to build new infrastructure and the hardware and software already existing.
- Lower risk arises from the fact that the cellular user base already exists while DSRC infrastructure must be deployed and requires huge investments. The added cost of equipment in cars could be risky if the consumer does not see the additional benefit compared to what the applications on their cellphone could provide.

An optimum solution may be to have a DSRC network for V2V communication complemented by a cellular network (preferably LTE) as a backup solution to address the V2I needs.

13.7 Deployment Readiness

The performance of applications and bundles improve as more and more vehicles get equipped. For this assessment, the team used a combination of qualitative and quantitative assessment to see whether applications are ready to be deployed in the field and how far in to the future are benefits achievable. Qualitative analysis was performed by mapping the data elements required by different prototyped applications and the data elements that are not currently in the BSM message sets. In order to assist with the quantitative assessment, the team used NHTSA’s approach to map near-, mid- and long-term deployments based on a variety of factors such as deployment costs, fuel costs, fleet composition, fleet age and turnover etc. and mapped them to the market penetration used this this project.

Qualitative assessment showed that most of the DMA applications, with the exception of Individual DMA applications require connected vehicle data elements beyond BSM for its functioning. The quantitative assessment showed maximum increase in benefits under near-term, when the CV market penetration is up to 55 percent, beyond which the rate of increase in benefits slows down.

13.8 Analysis of Benefits and Deployment Costs

This chapter analyzed the costs and benefits associated with each DMA application/bundle on San Mateo and Phoenix region using a cost-benefit model developed by the DMA Program Evaluation team for National-Level Impact Estimation. As shown in this chapter, benefits and costs from this model cannot be used in a trade-off analysis, since costs developed does not account for shared costs as well as costs for deployment of DMA applications as a supplement to other applications. In addition, the costs used in this model are from the CO-PILOT tool which is only meant for high-level estimation for pilot projects and not for full-fledged deployments. However, under lack of other sources and specific assumptions made, the team evaluated the deployment costs and value of benefits from individual applications by adapting a national level model to a regional scale. Table 12-1 provides a summary of deployment costs and value of benefits associated with applications

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	T-DISP	2	1.1

*Deployment Costs are assessed when implemented as non-shared deployment.

Chapter 14. Limitations of the Analysis

The wide portfolio of testbed selections was populated with the goal of best evaluating DMA and ATDM strategies in mind. However, as with any experimental design, there are some limitations inherent in the approach that not all of the questions that this research set out to answer would be satisfactorily answered.

Each of the testbeds is a complex project that spans multiple pieces of software. For example, the San Mateo analysis consists of the following software: Vissim (as the micro-simulation tool), INFLO (DMA Application), Linux (providing intersection controller for MMITSS), TCA (providing communications emulation) etc. Generally, the risks at each testbed revolve around the individual software packages operating efficiently and achieving a reliable and efficient link between the software packages efficiently. Achieving these efficiencies reduces the risk that project resources are prematurely exhausted. In each testbed, these risks are mitigated through careful and thoughtful software systems architecture and experimental design. However, the complexity of integrating these tools has affected the run-time of simulations and therefore analyses had to be scaled down in terms of number of runs, analysis regions, and/or simulation time-line. For example, the TCA module slowed down the simulation to almost 0.2x real-time with 50 percent vehicles producing BSM messages. Therefore, the communications analysis only included peak-of-the-peak period analysis.

This chapter expands on the limitations of this analysis so that the audience has full insight in to the test conditions under which the evaluation was performed. A forth-coming publication titled “White Paper on AMS Gaps, Challenges, and Future Research” will provide additional insights into the gaps, challenges, and directions for future research to address these limitations.

14.1 Network Calibration to Real-World Conditions

The network calibration was performed based on the data from representative days given by a operational condition analysis procedure recommended by the soon-to-be published update to the FHWA Traffic Analysis Toolbox Volume III, Guidelines for Applying Traffic Microsimulation Modeling Software. Due to limited data, the San Mateo network was calibrated only for US-101 North Bound direction and was used in the analysis of freeway applications. The network was also calibrated for the El Camino Real, but used travel-time data from NPMRDS data source since traffic counts or turn-volume data was unavailable.

Additionally, the network does not allow dynamic routing between arterial and freeways since they were calibrated using independent statistics collected from the field and resulted in independent set of static paths. However, the testbed team developed additional routes near the ramps to account for rerouting vehicles during incident scenarios. However, these are not dynamic like in real-life. The team conducted limited analysis of MMITSS application when combined with freeway-based applications such as INFLO and INC-ZONE since they run independently of each other. Additional simulations with varying percentages of on-ramp and off-ramp demands were added to the scenarios to mitigate this limitation.

It has to be noted that the DMA applications are non-existent in real-life and therefore, the test scenarios were not calibrated to any existing case. The team performed rigorous visual audits during the implementation of these applications and performed adjustments to the network and applications to avoid unexpected network behavior.

As far as Phoenix testbed is concerned, the team was unable to acquire transit and freight data to build T-DISP and FRATIS models. For modeling T-DISP, assumptions were made regarding the transit demand using a mix of three fixed O-D paths – short, medium, and long, and were used in aggregating the impacts throughout the network.

14.2 Application-Specific Limitations

The INFLO analysis was based on the application developed for the Impact Assessment team by Texas Transportation Institute. The upgrades made to the application since the Impact Assessment was not added to the application used in this analysis. Additionally, the INFLO program was developed to run with Vissim 5.40. Modifications at the level of simulation inputs and outputs through Access Database Sockets were done when the analysis was performed using Vissim 6.00. For example, in Vissim 5.40, the simulation can output vehicle parameters to a Microsoft Access file in real-time. This feature was removed in Vissim 6.00. Therefore, COM was used to access vehicle parameters during simulation.

The MMITSS Application was simulated only in eight of the signal controllers in the El Camino Real arterial (San Mateo Network) owing to the large dependencies of the application to manually coding in the geographic limits of individual intersections. Additionally, the simulation run-time was 1x since Vissim's Econolite controllers face time-sync issues if the simulation was faster. This also restricted the number of simulation runs as well as the visual audits (which slows down the simulation).

The prototypes of three strategic DMA bundles/applications, namely, EnableATIS, FRATIS, and IDTO were not available for the team to use in this project, either due to schedule or dependencies with external programs. Therefore, the team developed these applications as part of this project using the respective System Design Document descriptions. These applications may not fully represent the prototyped applications owing to the limitations in developing them for a microsimulation environment. For example, FRATIS system prototyped does not contain the application Drayage Optimization (DR-OPT), since it is a pre-trip fleet scheduling tool which is difficult to model in a deterministic simulation model. The EnableATIS application considered only route-choice and not mode or departure time choice.

Communications modeling used in this project utilizes the TCA Tool developed by Noblis in conjunction with Vissim simulations. While TCA tool can analyze the impact of communication latency and losses as a constant input value, in real-life, these values depend on several factors such as a dynamic environmental function (temperature, humidity, presence of other radio waves etc.), distance between vehicles, distance from RSE units etc. Additional communication attributes such as impact of hidden nodes, physical obstacles such as buildings, roadway grade etc. are not considered.

Additionally, applications included in Phoenix Testbed were not derived from DMA Programs Prototype Development team. The Phoenix Team developed these applications based on the application description and the requirements that were previously published. The extend of how these applications represent real-life prototype applications are given below:

- EnableATIS application was developed as a DTA-Lite Tool. This application reroutes individual vehicles to an optimal route based on link-based travel times. Dependency on other factors such as weather is not included in this model. Additionally, the features such as departure-time and mode-choice changes are also not modeled in this application.

- FRATIS was developed as a DTA-Lite Tool. This application reroutes individual trucks to an optimal route based on link-based travel times. Additionally, the application also optimizes delivery and pick-up sequence when there are multiple delivery points. Features such as departure time adjustment, dependency on weather, terminal congestion etc. are not modeled in this application.
- T-DISP was also developed as a DTA-Lite Tool. This application enables dynamic dispatch of transit vehicles along a route based on traveler demand. Features such as dynamic transit routing to drop-off passengers and dynamic transit mode choice are not modeled.
- D-RIDE was developed as a proof-of-concept independent tool. Dynamic ride-sharing matches drivers and passengers based on vehicle capacities, location, departure and arrival times and was used to match 100 travelers with car-pools. The application is not fully integrated with DTALite, but provides a pre-optimization model to match traveler demand in the network. D-RIDE optimization can be visualized using NEXTA.

14.3 Simulation Limitations

The Booz Allen team performed at least five simulations for the San Mateo testbed using multiple random seeds for each scenario so that the results are statistically significant. Simulations using specific DMA applications and combinations were too slow and certain combinations require manual assistance to enable time-synchronization between applications. These scenarios could not be repeated more than 5 times due to time constraints. The team, hence, used fixed seed runs to have a better baseline comparison. For example, a fixed seed of “3”, when used for both baseline and test-scenario will produce comparable results since the start-up speed will impact the vehicle generation, behavior etc. in similar ways.

Performance of applications was assessed using certain application-specific performance measures that were not normally used for comparison of traffic simulations. The team utilized documentations from DMA Impact Assessment (IA) teams to identify these performance measures and checked for consistency in computation of these measures with the USDOT IA teams or documentations. For example, INFLO Impact Assessment teams suggested little statistical significance when using travel time savings or other mobility-based measures for performance measurement. Hence the team used “reduction in shockwaves” as the measure using the logic provided by the IA Teams.

There were several behavioral limitations when the DMA applications are adapted to a simulation-based evaluation. Certain applications are supposed to provide feedback to drivers and not actionable items. For example, queue warning application is supposed to just alert the driver of a downstream queue and it is up to the driver to decide the action. In real-life, this might include taking an exit and following alternate route. The simulation using Vissim, since is not a driver-based, but a vehicle-based, require vehicle-specific actionable commands. Therefore, queue-warning and speed-harmonization was combined to alter the desired speeds of vehicles. Similarly, instead of providing alerts and warnings to drivers, INC-ZONE application was adapted to alter the desired speed and lane-choice of vehicles. Additionally, the simulations assumed 100% driver compliance. In other words, all vehicles took action when generated by the DMA applications.

Chapter 15. Appendices

This chapter lists the appendices to this report. The following appendix sections can be found in the report:

Appendix A. Acronyms Used

The following table provides a comprehensive listing of acronyms used in this report.

Table A-1: Acronyms

Acronym	Expansion
4G	4th Generation Cellular Connection
5G	5th Generation Cellular Connection
AASHTO	American Associate of State Highway and Transportation Officials
ABS	Anti-lock Braking Systems
AMS	Analysis, Modeling and Simulation
API	Application Programming Interface
ASC/3	Advanced System Controller
ASU	Arizona State University
ATDM	Active Transportation and Demand Management
ATIS	Advanced Traveler Information System
BMM	Basic Mobility Message
BSM	Basic Safety Message
CACC	Cooperative Adaptive Cruise Control
CAGR	Compound Annual Growth Rate
CCTV	Closed Circuit Television
COM	Component Object Model
CO-PILOT	Cost Overview for Planning Ideas and Logical Organizational Tool
CV	Connected Vehicles
DEC	Decentralized
DFW	Dallas Fort Worth
DLL	Dynamic Link Library
DMA	Dynamic Mobility Applications
D-RIDE	Dynamic Ridesharing
DSRC	Dedicated Short Range Communication
DTA	Dynamic Traffic Assignment
EnableATIS	Enable Advanced Traveler Information Systems
EVAC	Evacuation Application
FCC	Federal Communications Commission
F-DRG	Freight Dynamic Route Guidance
FHWA	Federal Highway Administration
FRATIS	Freight Advanced Traveler Information Systems

Acronym	Expansion
FSP	Freight Signal Priority
HOV	High Occupancy Vehicles
IDTO	Integrated Dynamic Transit Operations
IEEE	Institute of Electrical and Electronics Engineers
INC-ZONE	Incident Scene Work Zone Alerts for Drivers and Workers
INFLO	Intelligent Network Flow Optimization
I-SIG	Intelligent Signal Control
LCC	Life Cycle Cost
LTE	Long Term Evolution
MAG	Maricopa Association of Governments
MMITSS	Multi-Modal Intelligent Traffic Signal Systems
MP	Market Penetration
NEXTA	Network Explorer for Traffic Analysis
NHTSA	National Highway Traffic Safety Administration
NTCIP	National Transportation Communications for ITS Protocol
OBU/OBE	On-Board Unit/Equipment
O-D	Origin Destination
OSADP	Open Source Application Development Portal
PDM	Probe Data Message
PED-SIG	Pedestrian Signal Control
PREEMPT	Emergency Vehicle Preemption
Q-WARN	Queue Warning
R.E.S.C.U.M.E.	Response, Emergency Staging and Communications, Uniform Management and Evacuation
RESP-STG	Incident Scene Pre-Arrival Staging Guidance for Emergency Responders
RSE	Road Side Equipment
RWIS	Road Weather Information Systems
SAE	Society of Automotive Engineers
SOV	Single Occupancy Vehicles
S-PARK	Smart Park and Ride
SPAT	Signal Phasing and Timing
SPD-HARM	Dynamic Speed Harmonization
TCA	Trajectory Converter Algorithm
T-CONNECT	Transit Connection Protection
T-DISP	Dynamic Transit Dispatch Operations
T-MAP	Transportation Map Application
TSP	Transit Signal Priority
TSS	Traffic Sensor Systems
TTI	Texas Transportation Institute OR Travel Time Index

Acronym	Expansion
UA	University of Arizona
USDOT	United States Department of Transportation
V2I	Vehicle to Infrastructure
V2V	Vehicle to Vehicle
VMS	Variable Message Signs
VMT	Vehicle Miles Traveled
VRP	Vehicle Routing Problem
WAVE	Wireless Access in Vehicular Environments
Wi-Fi	Wireless Fidelity
WX-INFO	Real Time Rout Specific Weather Information

Appendix B. Data Elements by Application

The following table provides a comprehensive listing of the data elements required by individual applications as prescribed in FHWA-JPO-12-021, Vehicle Information Exchange Needs for Mobility Applications.

Table A-2: Data Needs for Different DMA Applications

Bundle Name	App Name	Data Element	Message Type
EnableATIS	ATIS	Motion	BSM-1
EnableATIS	ATIS	Position (local 3D)	BSM-1
EnableATIS	ATIS	Vehicle size	BSM-1
EnableATIS	ATIS	ABS State	BSM-2
EnableATIS	ATIS	TCS State	BSM-2
EnableATIS	ATIS	Road coefficient of friction	BSM-2
EnableATIS	ATIS	Rain sensor	BSM-2
EnableATIS	ATIS	Lights changed	BSM-2
EnableATIS	ATIS	Wipers changed	BSM-2
EnableATIS	ATIS	Exterior lights status	BSM-2
EnableATIS	ATIS	Wiper status	BSM-2
EnableATIS	ATIS	Ambient air temperature	BSM-2
EnableATIS	ATIS	Ambient air pressure	BSM-2
EnableATIS	ATIS	Selected route and mode	
EnableATIS	ATIS	Directions and times by mode	
EnableATIS	ATIS	Departure location	
EnableATIS	ATIS	Destination	
EnableATIS	ATIS	Target departure time	
EnableATIS	ATIS	Target arrival time	
EnableATIS	S-PARK	Part and ride lot status info	
EnableATIS	T-MAP	Motion	BSM-1
EnableATIS	T-MAP	Position (local 3D)	BSM-1
EnableATIS	T-MAP	Vehicle size	BSM-1
EnableATIS	T-MAP	Location	
EnableATIS	WX-INFO	ABS State	BSM-2
EnableATIS	WX-INFO	TCS State	BSM-2
EnableATIS	WX-INFO	Road coefficient of friction	BSM-2
EnableATIS	WX-INFO	Rain sensor	BSM-2
EnableATIS	WX-INFO	Lights changed	BSM-2
EnableATIS	WX-INFO	Wipers changed	BSM-2
EnableATIS	WX-INFO	Exterior lights status	BSM-2

Bundle Name	App Name	Data Element	Message Type
EnableATIS	WX-INFO	Wiper status	BSM-2
EnableATIS	WX-INFO	Ambient air temperature	BSM-2
EnableATIS	WX-INFO	Ambient air pressure	BSM-2
FRATIS	DR-OPT	Assigned load pickup time	
FRATIS	DR-OPT	Assigned load drop off time	
FRATIS	DR-OPT	Change in pickup or drop off time	
FRATIS	DR-OPT	Load matching response	
FRATIS	DR-OPT	Pickup or drop off request	
FRATIS	DR-OPT	Load matching request	
FRATIS	F-ATIS	Motion	BSM-1
FRATIS	F-ATIS	Position (local 3D)	BSM-1
FRATIS	F-ATIS	ABS State	BSM-2
FRATIS	F-ATIS	TCS State	BSM-2
FRATIS	F-ATIS	Road coefficient of friction	BSM-2
FRATIS	F-ATIS	Rain sensor	BSM-2
FRATIS	F-ATIS	Lights changed	BSM-2
FRATIS	F-ATIS	Wipers changed	BSM-2
FRATIS	F-ATIS	Exterior lights status	BSM-2
FRATIS	F-ATIS	Wiper status	BSM-2
FRATIS	F-ATIS	Ambient air temperature	BSM-2
FRATIS	F-ATIS	Ambient air pressure	BSM-2
FRATIS	F-ATIS	Weather info for freight	
FRATIS	F-ATIS	Vehicle data	BSM-2
FRATIS	F-ATIS	Recent or current hard braking	BSM-2
FRATIS	F-ATIS	Confidence time	BSM-2
FRATIS	F-ATIS	Confidence position	BSM-2
FRATIS	F-ATIS	Confidence speed/heading/throttle	BSM-2
FRATIS	F-ATIS	Freight routing with travel times	
FRATIS	F-ATIS	Incident alerts	
FRATIS	F-ATIS	Road closure info	
FRATIS	F-ATIS	Work zone info	
FRATIS	F-ATIS	Freight routing restrictions	
FRATIS	F-ATIS	Regulatory and enforcement info	
FRATIS	F-ATIS	Info on concierge and maintenance services and locations	
FRATIS	F-DRG	ABS State	BSM-2
FRATIS	F-DRG	TCS State	BSM-2
FRATIS	F-DRG	Road coefficient of friction	BSM-2
FRATIS	F-DRG	Rain sensor	BSM-2
FRATIS	F-DRG	Lights changed	BSM-2
FRATIS	F-DRG	Wipers changed	BSM-2

Bundle Name	App Name	Data Element	Message Type
FRATIS	F-DRG	Exterior lights status	BSM-2
FRATIS	F-DRG	Wiper status	BSM-2
FRATIS	F-DRG	Ambient air temperature	BSM-2
FRATIS	F-DRG	Ambient air pressure	BSM-2
FRATIS	F-DRG	Vehicle placarded as HAZMAT carrier	BSM-2
FRATIS	F-DRG	Vehicle height	BSM-2
FRATIS	F-DRG	Vehicle mass	BSM-2
FRATIS	F-DRG	HAZMAT status	BSM-2
FRATIS	F-DRG	Vehicle type (fleet)	BSM-2
FRATIS	F-DRG	Descriptive Vehicle ID	BSM-2
FRATIS	F-DRG	Fleet Owner Code	BSM-2
FRATIS	F-DRG	Freight route guidance update	
FRATIS	F-DRG	Freight route guidance response	
FRATIS	F-DRG	Destination and stops	
IDTO	D-RIDE	Vehicle type (fleet)	BSM-2
IDTO	D-RIDE	ETA for pickup	
IDTO	D-RIDE	ETA at destination	
IDTO	D-RIDE	Target departure time	
IDTO	D-RIDE	Destination	
IDTO	D-RIDE	Target arrival time	
IDTO	D-RIDE	Amount willing to pay	
IDTO	D-RIDE	Departure location	
IDTO	D-RIDE	Cost	
IDTO	D-RIDE	Number of occupants in vehicle	
IDTO	T-CONNECT	Current itinerary	
IDTO	T-CONNECT	Connection protection response	
IDTO	T-CONNECT	Connection protection update	
IDTO	T-CONNECT	List of number of passengers by route	
IDTO	T-CONNECT	Passenger count	
IDTO	T-CONNECT	Schedule update	
IDTO	T-CONNECT	Status versus schedule	
IDTO	T-DISP	Passenger count	
IDTO	T-DISP	Revised Routes, including timing	
IDTO	T-DISP	Schedule update	
IDTO	T-DISP	Status versus schedule	
IDTO	T-DISP	Itinerary	
IDTO	T-DISP	Target time of arrival	
IDTO	T-DISP	Target time of departure	
IDTO	T-DISP	Location	
IDTO	T-DISP	Status versus schedule	

Bundle Name	App Name	Data Element	Message Type
IDTO	T-DISP	Request being responded to	
IDTO	T-DISP	Pickup location	
IDTO	T-DISP	Pickup time	
IDTO	T-DISP	Revised Routes, including timing	
IDTO	T-DISP	Destination time	
IDTO	T-DISP	Vehicle dispatched	
IDTO	T-DISP	Schedule	
INFLO	CACC	Vehicle size	BSM-1
INFLO	CACC	Brake system status	BSM-1
INFLO	CACC	Motion	BSM-1
INFLO	CACC	Position (local 3D)	BSM-1
INFLO	CACC	Road coefficient of friction	BSM-2
INFLO	CACC	Rain sensor	BSM-2
INFLO	CACC	TCS State	BSM-2
INFLO	CACC	ABS State	BSM-2
INFLO	CACC	Data/time of obstacle detection	BSM-2
INFLO	CACC	Azimuth to obstacle on the road	BSM-2
INFLO	CACC	Confidence position	BSM-2
INFLO	CACC	Confidence speed/heading/throttle	BSM-2
INFLO	CACC	Throttle position (percent)	BSM-2
INFLO	CACC	Trailer weight	BSM-2
INFLO	CACC	Confidence time	BSM-2
INFLO	CACC	Recent or current hard braking	BSM-2
INFLO	CACC	Level of brake application	BSM-2
INFLO	CACC	Vehicle data	BSM-2
INFLO	CACC	Distance to obstacle on road	BSM-2
INFLO	CACC	Hazard lights active	BSM-2
INFLO	CACC	Geocoded road segment	
INFLO	CACC	Gap recommendation by vehicle type	
INFLO	Q-WARN	Motion	BSM-1
INFLO	Q-WARN	Position (local 3D)	BSM-1
INFLO	Q-WARN	Type or speed of end of queue	
INFLO	Q-WARN	Location of end of queue	
INFLO	SPD-HARM	Motion	BSM-1
INFLO	SPD-HARM	Exterior lights status	BSM-2
INFLO	SPD-HARM	Ambient air temperature	BSM-2
INFLO	SPD-HARM	ABS State	BSM-2
INFLO	SPD-HARM	Ambient air pressure	BSM-2
INFLO	SPD-HARM	Wiper status	BSM-2
INFLO	SPD-HARM	Lights changed	BSM-2

Bundle Name	App Name	Data Element	Message Type
INFLO	SPD-HARM	Wipers changed	BSM-2
INFLO	SPD-HARM	Rain sensor	BSM-2
INFLO	SPD-HARM	Road coefficient of friction	BSM-2
INFLO	SPD-HARM	TCS State	BSM-2
INFLO	SPD-HARM	Level of brake application	BSM-2
INFLO	SPD-HARM	SPaT data	
INFLO	SPD-HARM	Target speeds by lane	
MMITSS	FSP	Motion	BSM-1
MMITSS	FSP	Position (local 3D)	BSM-1
MMITSS	FSP	Road coefficient of friction	BSM-2
MMITSS	FSP	Rain sensor	BSM-2
MMITSS	FSP	Lights changed	BSM-2
MMITSS	FSP	Wipers changed	BSM-2
MMITSS	FSP	Exterior lights status	BSM-2
MMITSS	FSP	Wiper status	BSM-2
MMITSS	FSP	Ambient air temperature	BSM-2
MMITSS	I-SIG	Motion	BSM-1
MMITSS	I-SIG	Position (local 3D)	BSM-1
MMITSS	I-SIG	Vehicle size	BSM-1
MMITSS	I-SIG	ABS State	BSM-2
MMITSS	I-SIG	TCS State	BSM-2
MMITSS	I-SIG	Road coefficient of friction	BSM-2
MMITSS	I-SIG	Rain sensor	BSM-2
MMITSS	I-SIG	Lights changed	BSM-2
MMITSS	I-SIG	Wipers changed	BSM-2
MMITSS	I-SIG	Exterior lights status	BSM-2
MMITSS	I-SIG	Wiper status	BSM-2
MMITSS	I-SIG	Ambient air temperature	BSM-2
MMITSS	I-SIG	Ambient air pressure	BSM-2
MMITSS	I-SIG	Weather info for freight	
MMITSS	I-SIG	Vehicle type (fleet)	BSM-2
MMITSS	I-SIG	Stop line violation	
MMITSS	PED-SIG	Public safety vehicle responding to emergency	
MMITSS	PED-SIG	Light bar in use	BSM-2
MMITSS	PED-SIG	Siren in use	BSM-2
MMITSS	PED-SIG	Approach road to intersection	
MMITSS	PED-SIG	Intended turning movement at intersection	
MMITSS	PED-SIG	Pedestrian location	
MMITSS	PED-SIG	Pedestrian intended crossing direction	
MMITSS	PED-SIG	Crossing status	

Bundle Name	App Name	Data Element	Message Type
MMITSS	PED-SIG	Crossing heading correction	
MMITSS	PREEMPT	Motion	BSM-1
MMITSS	PREEMPT	Position (local 3D)	BSM-1
MMITSS	PREEMPT	Public safety vehicle responding to emergency	
MMITSS	PREEMPT	Approach road to intersection	
MMITSS	PREEMPT	Intended turning movement at intersection	
MMITSS	TSP	Position (local 3D)	BSM-1
MMITSS	TSP	Motion	BSM-1
MMITSS	TSP	Passenger count	
MMITSS	TSP	Transit service type	
MMITSS	TSP	Approach road to intersection	
MMITSS	TSP	Intended turning movement at intersection	
MMITSS	TSP	Status versus schedule	
R.E.S.C.U.M.E.	EVAC	Position (local 3D)	BSM-1
R.E.S.C.U.M.E.	EVAC	Vehicle dispatched	
R.E.S.C.U.M.E.	EVAC	Schedule	
R.E.S.C.U.M.E.	EVAC	Origin	
R.E.S.C.U.M.E.	EVAC	Destination	
R.E.S.C.U.M.E.	EVAC	Desired mode	
R.E.S.C.U.M.E.	EVAC	Route information	
R.E.S.C.U.M.E.	EVAC	Evacuation routes information	
R.E.S.C.U.M.E.	EVAC	Road conditions	
R.E.S.C.U.M.E.	EVAC	Traffic reports	
R.E.S.C.U.M.E.	EVAC	EVAC information request	
R.E.S.C.U.M.E.	EVAC	Locations for lodging, food, water, fuel, cash machines etc.	
R.E.S.C.U.M.E.	EVAC	Special needs	
R.E.S.C.U.M.E.	EVAC	EVAC help response	
R.E.S.C.U.M.E.	INC-ZONE	Motion	BSM-1
R.E.S.C.U.M.E.	INC-ZONE	Position (local 3D)	BSM-1
R.E.S.C.U.M.E.	INC-ZONE	Lane closure information	
R.E.S.C.U.M.E.	INC-ZONE	Incident or work zone speed limit	
R.E.S.C.U.M.E.	RESP-STG	Position (local 3D)	BSM-1
R.E.S.C.U.M.E.	RESP-STG	Motion	BSM-1
R.E.S.C.U.M.E.	RESP-STG	Vehicle size	BSM-1
R.E.S.C.U.M.E.	RESP-STG	ABS State	BSM-2
R.E.S.C.U.M.E.	RESP-STG	TCS State	BSM-2
R.E.S.C.U.M.E.	RESP-STG	Road coefficient of friction	BSM-2
R.E.S.C.U.M.E.	RESP-STG	Rain sensor	BSM-2
R.E.S.C.U.M.E.	RESP-STG	Lights changed	BSM-2
R.E.S.C.U.M.E.	RESP-STG	Wipers changed	BSM-2

Bundle Name	App Name	Data Element	Message Type
R.E.S.C.U.M.E.	RESP-STG	Exterior lights status	BSM-2
R.E.S.C.U.M.E.	RESP-STG	Wiper status	BSM-2
R.E.S.C.U.M.E.	RESP-STG	Ambient air pressure	BSM-2
R.E.S.C.U.M.E.	RESP-STG	Ambient air temperature	BSM-2
R.E.S.C.U.M.E.	RESP-STG	Vehicle type (fleet)	BSM-2
R.E.S.C.U.M.E.	RESP-STG	Airbag deployment	BSM-2
R.E.S.C.U.M.E.	RESP-STG	Hazard lights active	BSM-2
R.E.S.C.U.M.E.	RESP-STG	Recent or current hard braking	BSM-2
R.E.S.C.U.M.E.	RESP-STG	Crash delta V	
R.E.S.C.U.M.E.	RESP-STG	Occupant safety belt use	
R.E.S.C.U.M.E.	RESP-STG	Number of occupants in vehicle	
R.E.S.C.U.M.E.	RESP-STG	Estimated point of impact	
R.E.S.C.U.M.E.	RESP-STG	Vehicle fuel type	
R.E.S.C.U.M.E.	RESP-STG	Vehicle resting position	
R.E.S.C.U.M.E.	RESP-STG	Occupant medical data	
R.E.S.C.U.M.E.	RESP-STG	Electronic manifest	
R.E.S.C.U.M.E.	RESP-STG	Staging plans	
R.E.S.C.U.M.E.	RESP-STG	Satellite imagery and GIS data	
R.E.S.C.U.M.E.	RESP-STG	Still and video images	
R.E.S.C.U.M.E.	RESP-STG	Road conditions	
R.E.S.C.U.M.E.	RESP-STG	Traffic reports	
R.E.S.C.U.M.E.	RESP-STG	Info on emergency centers	
R.E.S.C.U.M.E.	RESP-STG	Weather information including winds	
R.E.S.C.U.M.E.	RESP-STG	Segments and lanes plowed	

Appendix C. INFLO Modeling Details

The USDOT Dynamic Mobility Applications (DMA) Program focuses on exploring new forms of data from wirelessly connected vehicles, travelers, and the infrastructure to enable transformative mobility applications including advanced information systems for travelers and freight, incident management systems, and advanced management systems for highway facilities, transit, and signal control systems. The purpose of the Intelligent Network Flow Optimization (INFLO) is to facilitate concept development and needs refinement for the INFLO application and to assess their readiness for development and testing. The three applications under the INFLO bundle will ultimately help to maximize roadway system productivity, enhance roadway safety and capacity, and reduce overall consumption. These three applications are:

- Queue Warning (Q-WARN)
- Dynamic Speed Harmonization (SPD-HARM)
- Cooperative Adaptive Cruise Control (CACC).[41]

Speed Harmonization/Queue Warning

The INFLO Q-WARN application concept aims to minimize the occurrence and impact of traffic queues by utilizing connected vehicle technologies, including vehicle-to-infrastructure (V2I) and vehicle-to-vehicle (V2V) communications, to enable vehicles within the queue event to automatically broadcast their queued status information (e.g., rapid deceleration, disabled status, lane location) to nearby upstream vehicles and to infrastructure-based central entities (such as the TMC) in order to minimize or prevent rear-end or other secondary collisions. The overall concept for the Q-WARN application is illustrated in the following Figure.

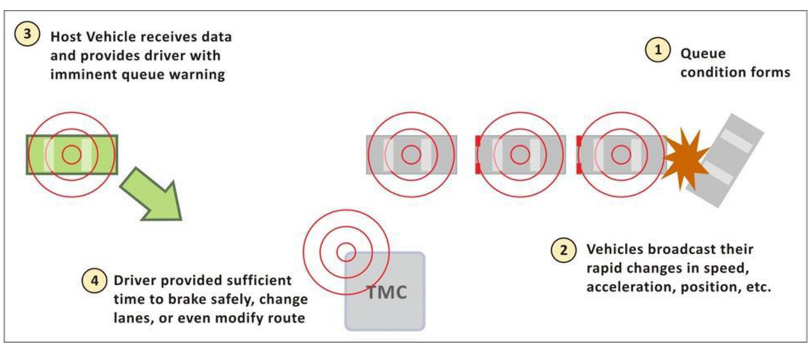

Figure A-1: Illustration of the Q-WARN Application[42] [Source: Booz Allen]

[41] "Concept Development & Needs Identification for Intelligent Network Flow Optimization (INFLO): Functional and Performance Requirements, and High Level Data and Communication Needs," Final Report FHWA-JPO-13-013, November 2012.

[42] Concept of Operations, Concept Development and Needs Identification for Intelligent Network Flow Optimization, Final
Report, FHWA-JPO-13-012, June, 2012

SPD-HARM application dynamically adjusts and coordinates vehicle speeds in order to maximize traffic throughput and reduce crashes. By reducing speed variability among vehicles, traffic throughput is improved, flow breakdown formation is delayed or even eliminated, and collisions and severity of collisions are reduced. The concept of SPD-HARM is that harmonizing the speeds of traffic flows in response to downstream congestion, incidents, and weather or road conditions can greatly help to maximize traffic throughput and reduce crashes. The INFLO SPD-HARM application concept aims to realize these benefits by utilizing connected vehicle communication to detect the precipitating roadway or congestion conditions that might necessitate speed harmonization, to generate the appropriate response plans and speed recommendation strategies for upstream traffic, and to broadcast such recommendations to the affected vehicles. Roadway sensors and connected vehicles transmit information on vehicle speeds, flow rates, and occupancy to the traffic management center (TMC). A road weather information system (RWIS) transmits facility information on visibility, coefficient of pavement-tire friction, temperature (air and road surface), humidity, wind speed, pressure, and precipitation to the connected vehicle and/or the TMC. The SPD-HARM application detects the presence of a mobility problem or predicts an imminent mobility problem based on heavy flow rates. A response-generating algorithm within the SPD-HARM application (housed at the TMC) recommends speeds for upstream vehicles and other recommended actions on the part of the TMC. This algorithm identifies the timing, location, and recommended speeds for transmission. The speed recommendations are transmitted to the vehicles on the facility.

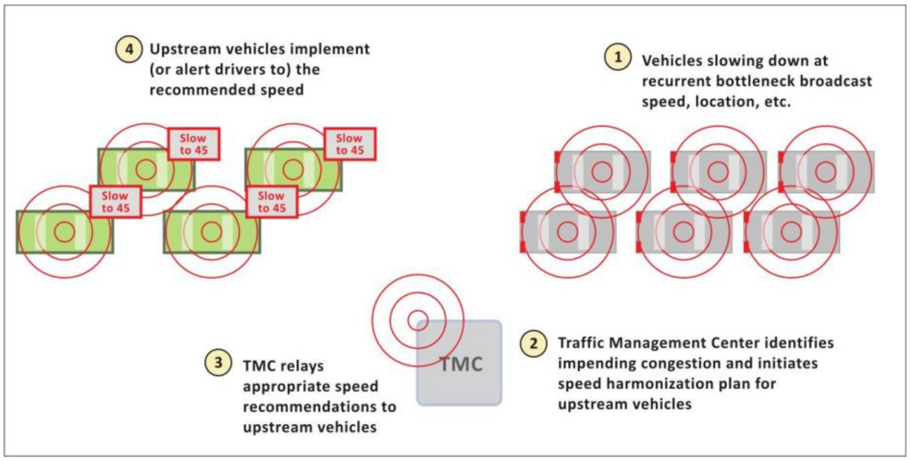

Figure A-2: SPD-HARM Concept with the Connected Vehicles[43] [Source: Booz Allen]

Modeling Details

The team utilized the application that is developed by the Texas Transportation Institute for DMA Impact Assessment in this project. The Q-WARN and SPD-HARM applications used in this assessment makes the following assumptions: [44]

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[43] Source: Concept of Operations, Concept Development and Needs Identification for Intelligent network Flow Optimization, Final Report, FHWA-JPO-13-012, June, 2012

[44] Kevin Balke, Hassan Charara, Srinivasa Sunkari; draft Report on Dynamic Speed Harmonization and Queue Warning Algorithm Design, Texas A&M Transportation Institute, FHWA, Washington, DC, January 15, 2014.

- Existing average traffic speeds by direction for each 1/10th-mile-long sublink of the facility are gathered from both infrastructure sensors and connected vehicles. In cases of conflicts between road sensors and connected vehicles, the lower speed controls.
- If a sufficient number and percent of roadway lane sensors or connected vehicles meet a user-set maximum speed threshold for being in queue state for a user-set sufficient length of time (to avoid false alarms), then the sublink is determined to be in the queue state.
- For each queue, a queue warning message is broadcast to all connected vehicles within a user-specified distance upstream of the back of the queue.
- The message states the distance between the vehicle and the back of the queue.
- Adjacent sublinks with similar mean speeds (falling within a speed range specified by the agency operator) are grouped together into "troupes."
- The recommended speed for each "troupe" is set at the average speed for that troupe rounded up to the nearest 5 mph increment, subject to:
  - Agency-specified maximum and minimum speed values for the sublinks cannot be exceeded.
  - The recommended speed cannot exceed the recommended maximum speed for weather condition
  - Differences in recommended speeds between adjacent troupes greater than 5 mph must be transitioned through the sublinks bordering the two adjacent troupes.
  - The recommended speed for any sublink cannot change more often than once every 15 seconds.
- The recommended connected vehicle speeds should be the same as that displayed on any roadway variable speed signs.
- Recommended speeds are advisory, not regulatory.
- The SPD-HARM prototype is always operational. There is always a recommended speed displayed (which may be zero for links with low measured speeds) for every sublink of the facility.
- The SPD-HARM prototype does not predict events nor speeds, and only recommends a speed significantly different from the measured average speed in the case of bad weather.

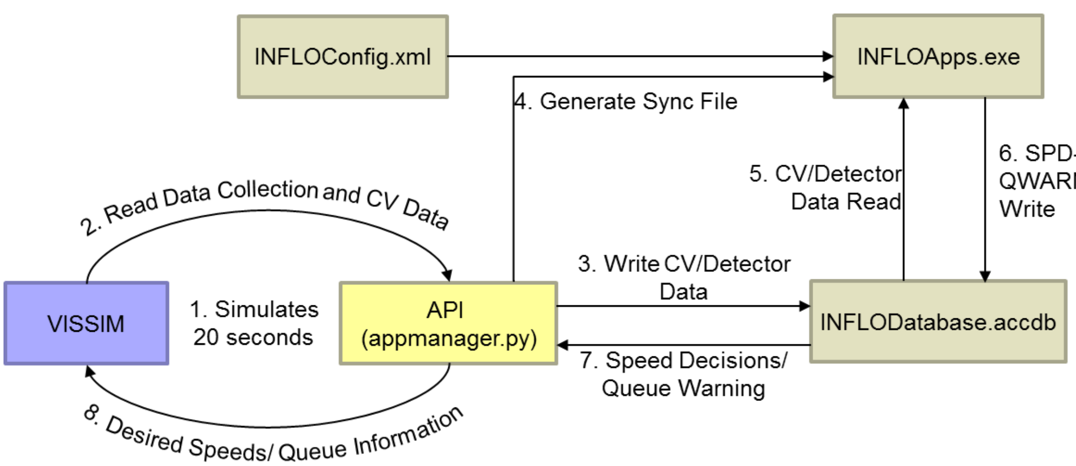


Figure A-3: Vissim Integration of INFLO in AMS Testbeds [Source: Booz Allen]

Figure A-3 shows how the INFLO Application is modeled in San Mateo Vissim network.

1. The simulation manager API (app manager) initiates the simulation and stops it every 20 seconds, assuming the INFLO application frequency to be 20-seconds.
2. The app manager uses Vissim's COM functionalities to query the data collection points for speed, volume and occupancy and the vehicles under CV class for location, speed, and heading.
3. The app manager writes these data (CV data and detector data) to the Access Database, which will serve as the Input / Output socket to the INFLO application.
4. Once the data is written to the database, the app manager generates a sync-file. The sync-file location is a location watched by the INFLO application and upon detecting the file. The application will start its computation based on the configuration settings defined in INFLOConfig.xml file.
5. When INFLO application is triggered (as in Step 4), the application will read the CV and Detector records from the database and computes harmonized speeds for each of the 0.1-mile long sublink and generates queue-warning.
6. The INFLO application then writes these speeds and queue information to the database.
7. The app manager reads the speed recommendations and the queue information generated in the database and converts them to vehicle-specific commands and desired speed decisions.
8. The app manager uses Vissim's COM interface to provide vehicle-specific commands and alter the class-specific desired speeds at specific desired speed locations.

Appendix D. R.E.S.C.U.M.E. Modeling Details

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. R.E.S.C.U.M.E. bundle consists of three different applications:

1. **EVAC** application supports region-wide evacuations. For those using their own transportation, it provides dynamic route guidance information and for those requiring assistance, it provides information to identify and locate people require guidance and assistance),
2. **RESP-STG** is a responder staging application and aims at enhancing the situational awareness of and coordination among emergency responders by providing valuable inputs to responder and dispatcher decisions and actions,
3. **INC-ZONE** is an incident zone application and warns drivers that are approaching temporary work zones at unsafe speeds and/or trajectory. It also warns public safety personnel and other officials working in the zone.

The Booz Allen team implemented the INC-ZONE applications as part of the San Mateo testbed. This application uses Vissim's COM capability to continuously monitor vehicle speeds and uses the threat-determination logic described in the System Design Document to issue vehicle commands to reduce desired speed and change desired lane selection parameters of vehicles. The code used is similar to what was used in the DMA Impact Assessment project.

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. **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.

Modeling INC-ZONE Features

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.

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.

As shown in Figure A-4, INC-ZONE application is managed by the appmanager which reads the vehicle parameters using COM and sends the vehicle table to the INC-ZONE Function. This function finds the vehicles which are within the alert, warning, or advisory distances for the incident defined in the INC-ZONE Configuration file. This step is called “Threat Determination”. Vehicles without any threat are ignored and the other vehicles are issued speed or lane-change commands based on their distance from the incident and their relative lane positions. The appmanager generates these commands and feeds to the Vissim simulation using desired lane and desired speed functions in COM. The application code is available in the Open Source Applications Development Portal (OSADP) at www.itseforge.net.

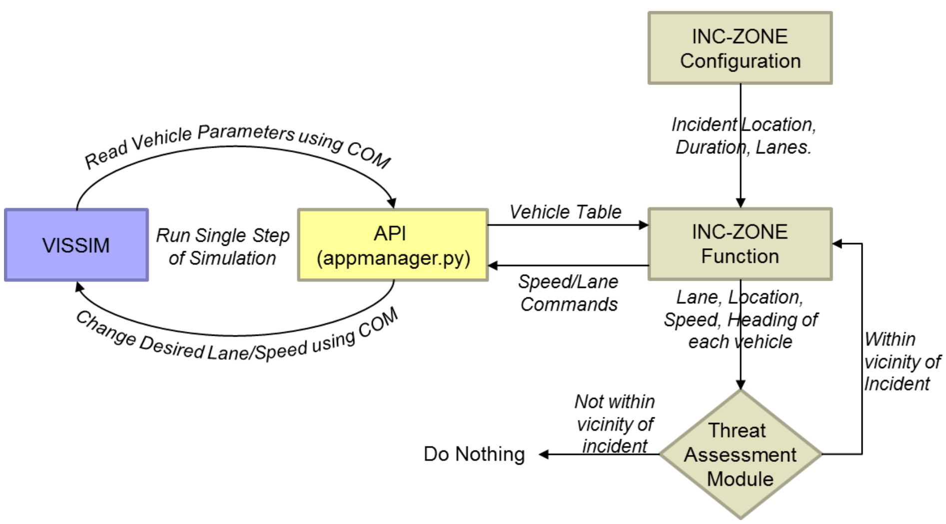


Figure A-4: Modeling of INC-ZONE Application in Vissim [Source: Booz Allen]

Appendix E. MMITSS Modeling Details

Multi-Modal Intelligent Traffic Signal Systems bundle (MMITSS) is a next-generation traffic signal system that seeks to provide a comprehensive traffic information framework to service all modes of transportation. Figure A-5 illustrates an example of the MMITSS application framework where different entities at a signalized intersection could interact using connected vehicle technology.

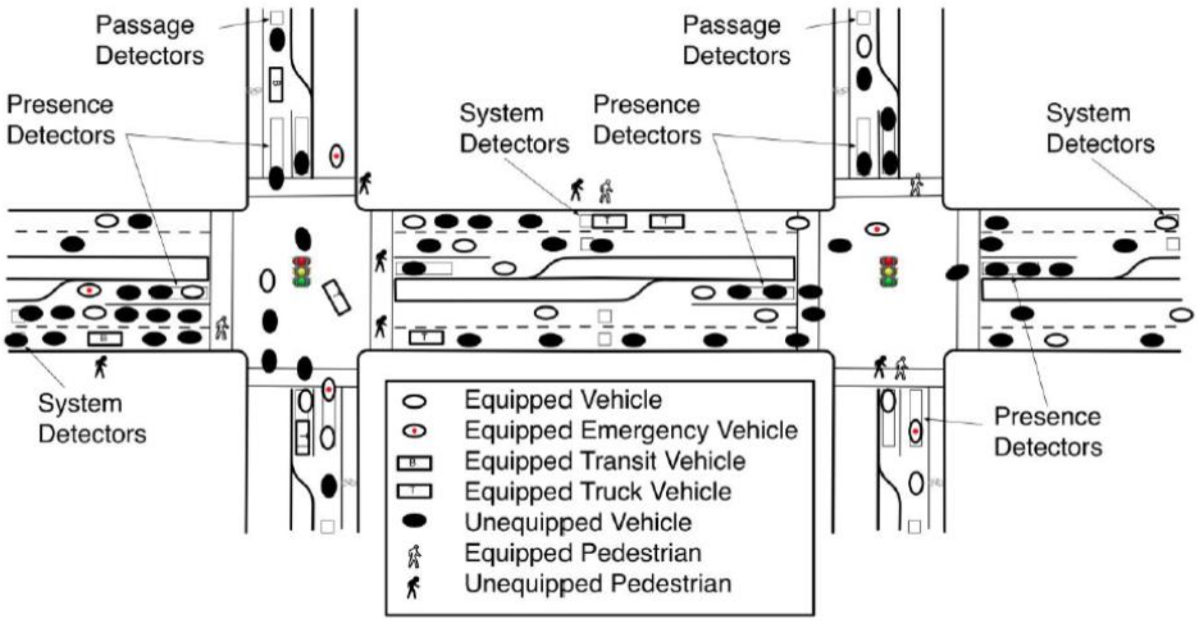


Figure A-5: Illustration of the MMITSS Concept[45] [Source: University of Arizona]

MMITSS consists of five different applications which all are prototyped together as a single MMITSS application by University of Arizona as a Software-in-the-Loop system. The five applications are described below and are modeled using combinations of functions that are turned on in Linux-based Docker Containers.

1. **I-SIG** aims at maximizing the throughput of passenger vehicles and minimizing the delay of priority vehicles under saturated conditions and minimizing the total weighted delay during under-saturated conditions.
2. **TSP** allows transit agencies to manage bus service by adding the capability to grant buses priority.
3. **PED-SIG** integrates information from roadside or intersection sensors and new forms of data from pedestrian-carried mobile devices.
4. **PREEMPT** will integrate with V2V and V2I communication systems in preempting signal phases for emergency vehicles.
5. **FSP** provides signal priority near freight facilities based on current and projected freight movements.

[45] Multi-Modal Intelligent Traffic Signal Systems (MMITSS) Impacts Final Report, USDOT, FHWA-JPO-15-238

Booz Allen team has acquired the MMITSS system from University of Arizona. The MMITSS system is a software in the loop system (SILS) and uses Vissim's Econolite/ASC3 control system to replace the innate signal control behavior using specifically designed Docker containers. The system also uses two inputs: Loop-detector inputs and connected vehicle data. Loop detector inputs are collected using data collection devices at intersection approaches. Driver behavior model in Vissim is used to read vehicle data and generate BSM to provide connected vehicle inputs to the MMITSS system. The setup is shown in Figure A-6.

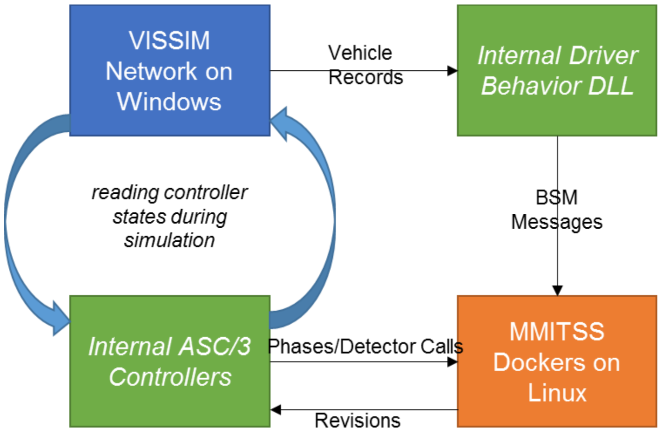


Figure A-6: MMITSS Integration in AMS Testbeds [Source: Booz Allen]

As shown in Figure A-6, the MMITSS is modeled as a complex Software-in-the-Loop System (SILS) to mimic real-world controller operations. The MMITSS application is coded to Docker Containers which are issued specific sub-net IP addresses and require two forms of inputs.

1. The ACS/3 controllers in Vissim are coded to communicate with these containers using their IP addresses which will provide them with phasing and detector call inputs as NTCIP 1202 objects.
2. The other input is provided by the vehicles itself in the form of Basic Safety Messages. BSMs are generated by the CV class of vehicles using BSM-generating driver-behavior models. These models communicate the BSMs to a BSM emulator which classifies them to the Road-Side-Equipment which is in its range. Based on the RSE-mapping, each of these BSMs go to their specific MMITSS containers to form the second set of inputs.

Using these two inputs, the containers produce NTCIP commands to intelligently control the ASC/3 controllers which are provided as output to the specific controller files.

MMITSS Components:

MMITSS application suite consists of two major components – The On-Board Unit (OBU) and Road-Side Unit (RSU) and each of these components have multiple sub-components within it as shown in Figure A-7. For the SILS set up of the application, there are two interfaces between the Vissim simulation and the MMITSS-enabled Docker-based applications – (a) interface to communicate BSM messages to the MMITSS for Intelligent Signal Control and (b) interface to communicate "revised" signal timing back to the simulation. These are explained below:

a. The BSM Distributor works by detecting vehicles within the vicinity of intersections and sending this data to that controller's Listener port as shown in Figure A-8.

b. The Traffic Controller Interface interfaces the MMITSS application output to the traffic controller in the simulation. At a high-level, this component is responsible for receiving signal timing schedule from the controller (MinGreen, MaxGreen, Yellow, and Red for all 8 phases) and send control commands back (NTCIP: FORCE_OFF, VEH_CALL, PHASE_OMIT, PHASE_HOLD).

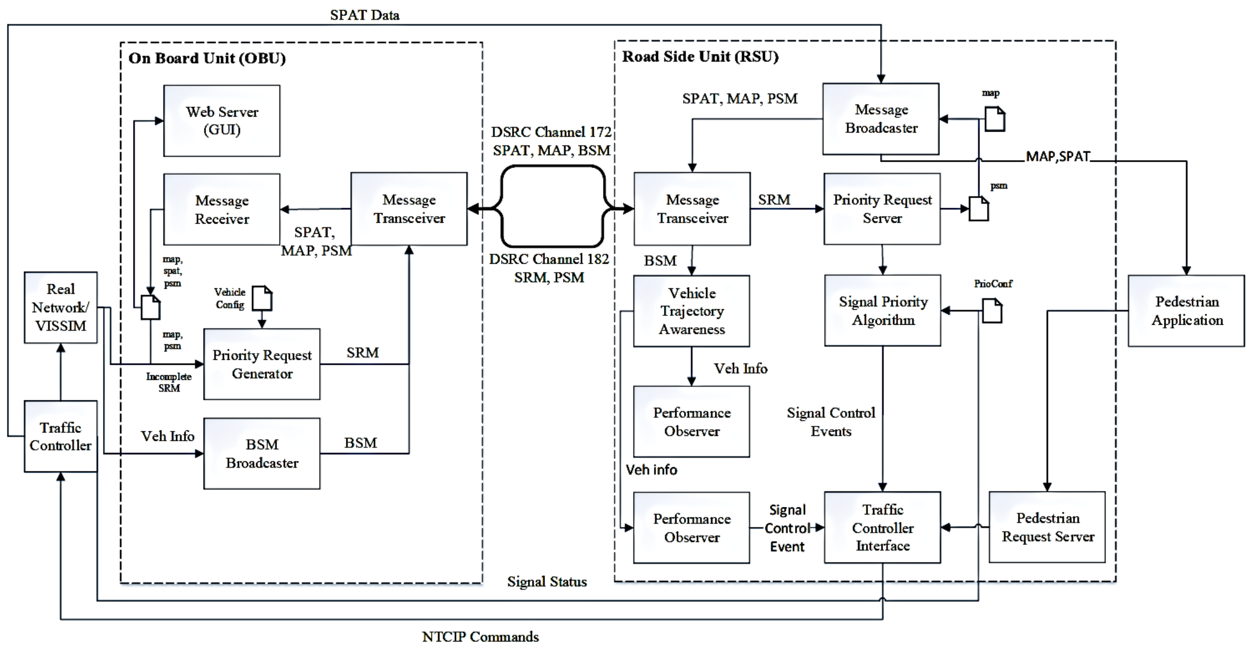


Figure A-7: MMITSS Component Diagram [Source: University of Arizona]

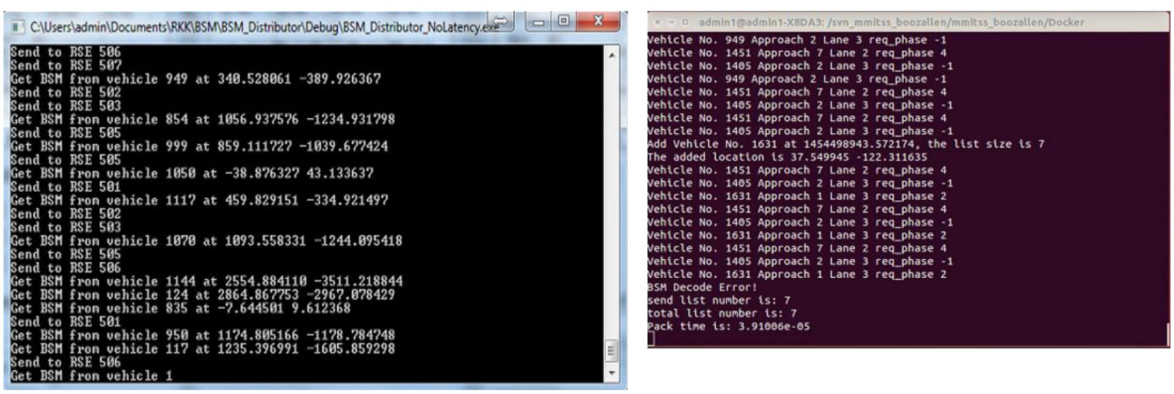


Figure A-8: (Left) BSM Distributor in Windows and (Right) BSM Receiver in Linux [Source: Booz Allen]

Vissim Implementation Pseudocode:

Below is a step-by-step simplified pseudocode of how MMITSS is currently implemented in Vissim:

1. CV class of vehicles will use a “driver-behavior model,” which communicates vehicle speed, position to a PORT as shown in Figure A-8.
2. BSM Distributor will “listen” to this PORT and distributes the vehicles to multiple controller PORTS which are connected to specific MMITSS containers as shown in Figure A-8.
3. Signal Controllers within Vissim are also connected to specific MMITSS container PORTS to read NTCIP commands and write the signal plans to them as shown in Figure A-9.
4. Once simulation is initiated, steps 2 and 3 will contribute enough data to MMITSS containers for them to generate commands for changing the signal phases in a desired way as shown in Figure A-10.

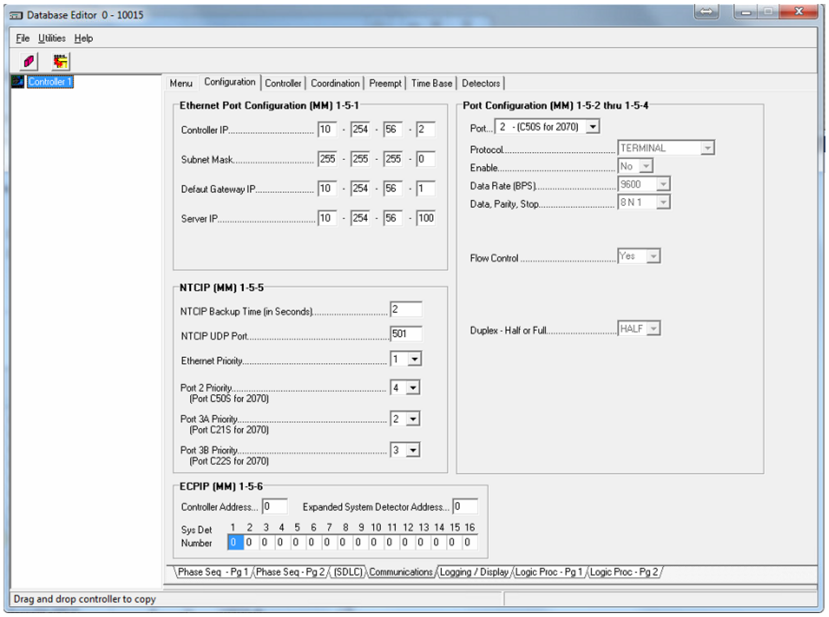


Figure A-9: Setting up Controllers to Read/Write to a Port [Source: Booz Allen]

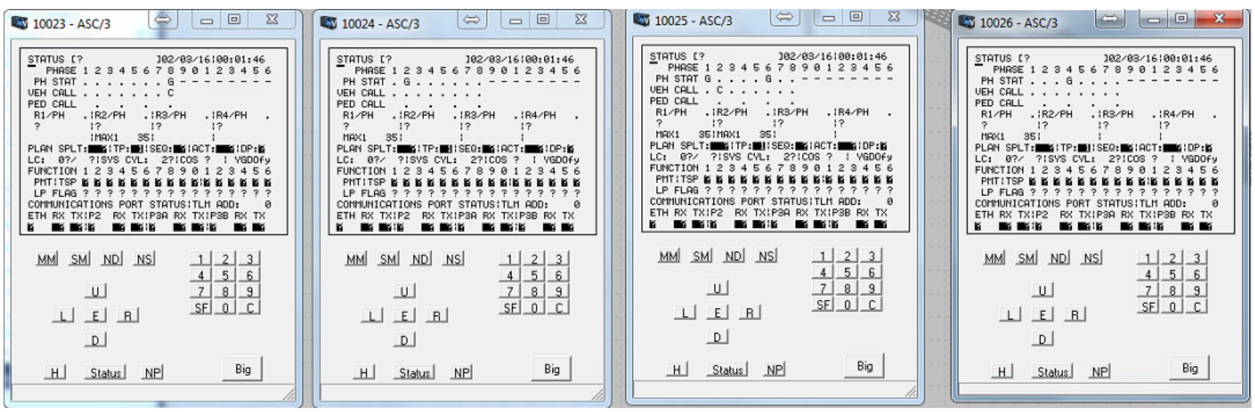


Figure A-10: Virtual Controllers Initiated for Each Intersection [Source: Booz Allen]

Appendix F. EnableATIS Modeling

Since the EnableATIS (Enabling Advanced Traveler Information Services) application was not previously prototyped and is developed as part of the AMS testbed project, the modeling details and algorithm is summarized in this appendix chapter. EnableATIS was developed by Arizona State University for implementation in the Phoenix testbed.

According to USDOT's goals[46], EnableATIS will intuitively provide users with trip, location, and mode-specific information to empower real-time decision making. The transportation networks will experience measurable gains in performance, including mobility, safety, and efficiency. Newly emerging technologies, such as connected vehicle or mobile computing devices, will allow travelers to check the real-time traffic condition and decide the most appropriate routes before they travel. New technologies also allow travelers to switch to alternative routes if they are aware of the congestions ahead along their current routes. These new technologies will definitely bring measurable benefits to the overall traffic network. In this project, instead of simulating the specific new technologies in EnableATIS, we focus on simulating the results brought by EnableATIS. EnableATIS can result in two major benefits – higher-fidelity traffic data for managers to understand the traffic pattern, and richer information for travelers to determine routes. From the perspective of simulation, the first benefit has been simulated and applied to various result analysis in the past, (Eg. Proactive Traffic Management) whereas implementing the second benefit in simulation requires additional route decision algorithms for each simulated traveler during simulation.

Two major benefits can be brought to travelers via EnableATIS: better pre-trip route planning based on the real-time traffic conditions and possible en-route path switching to avoid the bottleneck downstream of the road.

Specifically, the evaluation is performed as the following plan:

Step 1: Historical traffic pattern generation: Based on the calibrated network, DTALite will run multiple times to reach the initial user-equilibrium (UE) condition and travelers decide their routes according to the UE condition. Travelers without EnableATIS select routes according to the UE traffic condition.

Step 2: Introduce non-recurrent bottlenecks according to the incidents/accidents log from Arizona DOT on the corresponding day. As a result, additional congestion will be created around those bottlenecks and these real-time traffic changes will be aware by those travelers with EnableATIS. If those informed travelers have not departed, they will re-plan their routes to avoid congestions and if the informed travelers are on the roads, they will be able to re-plan their remaining routes to destinations to avoid congestions.

Step 3: Select different penetration rates of EnableATIS and evaluate the system-wide as well as near-the-bottlenecks congestion reductions.

During the simulation, travelers with EnableATIS may have two types of information: Pre-trip information and en-route re-routing suggestions. Before departure, EnableATIS allows travelers to examine the latest traffic conditions as well as obtain the updated route guidance for them to reach destinations to minimize the travel cost (e.g., travel time). As a result, some travelers in simulation will be assigned an alternative route rather than the historical routes obtained from the user-equilibrium condition. Furthermore, every 10

[46] http://www.its.dot.gov/dma/dma_development.htm#enableATIS

minutes, those travelers who have enter the road network will receive re-routing suggestions from EnableATIS if switching to an alternative route will save much travel time.

Modeling of EnableATIS

EnableATIS aims at providing time-dependent shortest path from origin to destination for travelers (pre-trip planning) or from the current location to destination (en-route rerouting). Therefore, seeking the shortest path in space-time network is advantageous over physical networks and the modelling efforts in EnableATIS are based on space-time network. Consider a directed, connected traffic network (N, E), where N is a finite set of nodes, and E is a finite set of traffic links between different adjacent nodes as shown in Figure A-11. The planning time horizon is discretized into a set of small time slots, denoted by $T = \{t0, t0 + \sigma, t0+2\sigma, ..., t0+M\sigma\}$. Symbol $t0$ specifies the given departure time from the origin node O, and σ represents a short time interval (e.g. 6 seconds) during which no perceptible changes of travel times are assumed to take place in a transportation network. M is a sufficiently large positive integer so that the time period from $t0$ to $t0+M\sigma$ covers the entire planning horizon.

For a given physical network, one can construct a corresponding space-time expanded network, denoted by (V, A), expanded from the physical network (N, E) and time-varying link travel time. Specifically, $V=\{(i,t)|i\in N,t\in T\}$ represents the set of time-dependent nodes, where $(i,t) \in V$ indicate the state of node i at time stamp t and each state will be treated as a separate node. The set of time dependent arcs is represented as $V=\{(i,j,t,s)|(i,j) \in E, t0\le t\le s\le t0+M\sigma\}$, where time dependent arc (i,j,t,s) occur in the space-time network when one can travel from physical node i at timestamp t and arrive at physical node j at timestamp s.

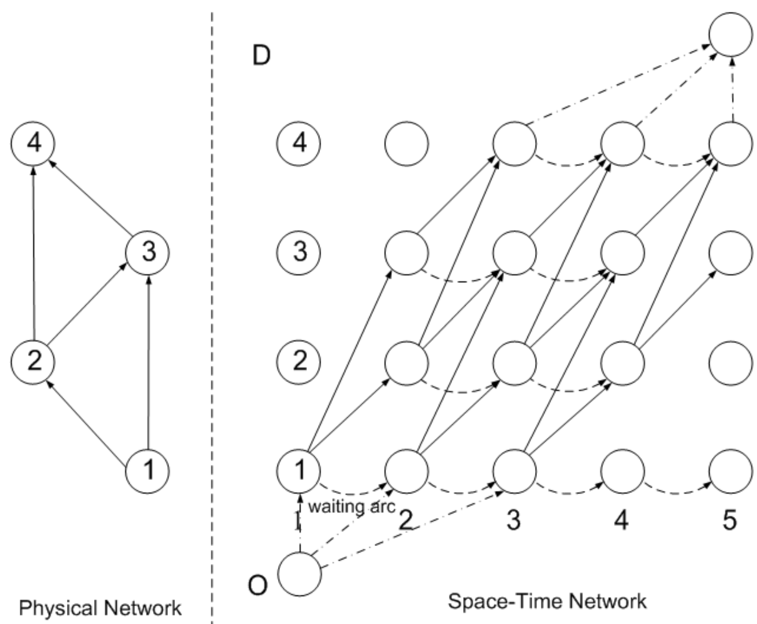


Figure A-11: Illustration of Physical Network and Space-Time Expanded Network [Source: Booz Allen]

As shown in Figure A-11, the plot on the left hand side exemplifies a physical network with assumed 1-minute travel time for each link, while the right hand side depicts its corresponding space-time network with a horizontal time dimension. Waiting arcs are introduced to model the situation of traveling agents staying at a node from one timestamp to the next, represented by dash lines in the figure. Source/sink nodes as well as super arcs from the super source and to the super sink (represented by dotted-dashed lines) are also shown. For simplicity, consider a point-queue model where each traveling agent is assumed to travel through a link at free-flow speed and waiting at the end node of the link if the inflow capacity of the subsequent link is unavailable. The point-queue model can be easily extended to the spatial queue and kinematic wave model, as shown by Zhou and Taylor (2014). A similar space-time representation was adopted by Yang and Zhou (2014) for an expected least travel time path problem where multiple days of observed link travel times are used to represent different random scenarios. This space-time structure can be also easily incorporated in the implementation for a dynamic network loading problem using agents.

Two most important decision variables in the agent-based optimization formulation, $y_{ij,ts}^{k}$and $z_{ij,ts}^{k}$, indicate whether agent k uses physical link *(i,j)* from time t to time s, along its Historical Info (HI) route or real-time Personalized Info (PI) route, respectively. Agents with PI are assumed to follow the navigation guidance optimized by the traffic system operator.

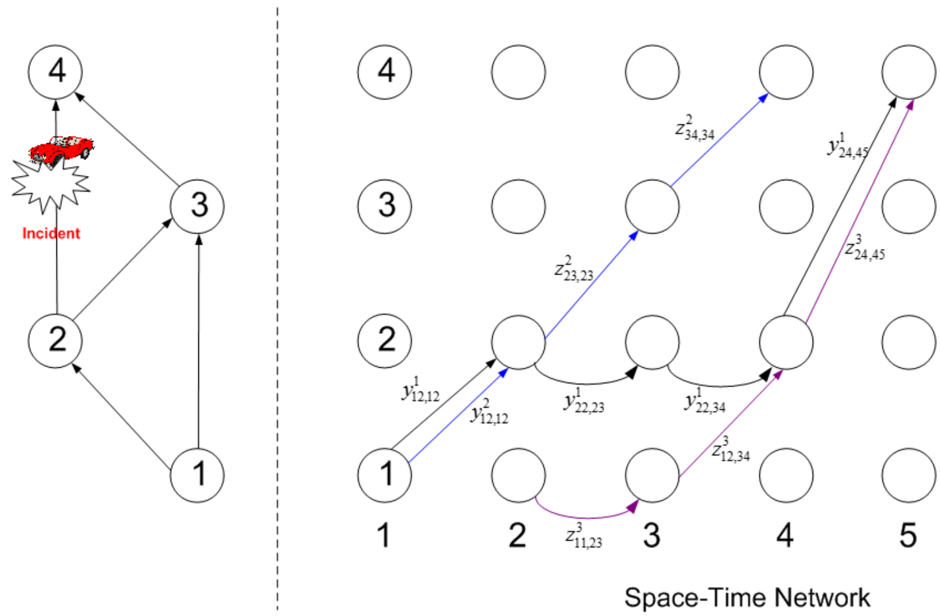


Figure A-12: Illustration of Decision Variables in a Multi-OD Space Time Network [Source: Booz Allen]

For example, in Figure A-12, three agents travel from node 1 to node 4 with a HI path as 1-2-4, with agent "1" and "2" starting at time = 1 and agent "3" starting at time = 2. An incident occurs on link (2,4) at time = 2 and last till time = 4. Without receiving any information updates, agent 1 still strictly follows the HI route and has to wait at node 2 for two units of time. Agent 2 receives real-time PI instructions at node 2 and minute 2, and then he/she follows the alternative route of 2-3-4 to avoid traffic congestion on link (2,4). With the same O-D and departure time, agent can save 1 unit of time in travel. Agent "3" receives real-time PI instructions at home before departure and then he/she waits for another 2 units of time at Origin. Although the planned departure time of agent "3" is one unit later than agent "1", it is able to arrive at the destination one unit earlier than agent "1". Agent "3" is suggested to wait at origin instead of at nodes of road network, since the generalized cost of waiting at home is much lower than waiting on the road. In terms of variable representation, agent "1" sets binary variable y to 1 along its traveling space-time trajectory, while agent “2” has y = 1 on link (1,2) and then its variable y is converted to variable z due to information provision. Another decision variable x_js represents the number of agents that receive PI information at node j and time stamp s. The sum of the variables x over different nodes j and different times s is equivalent to the total number of PI equipped travelers to be informed in the entire network.

The optimization of travelers on the space-time network is subject to multiple constraints as listed below:

1. Constraints on time-dependent network flows stating that the input should be same as output at each node.
   a. Flow balance constraints on origin node
   b. Flow balance constraints on destination node
   c. Flow balance constraints on intermediate node
2. Constraints on network propagation enables agent propagation by controlling link and node’s capacities.
   a. Inflow capacity constraints
   b. Continuous Flow constraints
3. Constraints on information provision constraints the amount of information available to vehicles/agents to control their dynamic routing, by controlling their short-term/long-term experiences, available VMS and other information etc.
   a. Information Activation Constraints
   b. Historical Information Provision Constraints
   c. Real-time Information Provision Constraints
   d. Node Information Provision Constraints
   e. Budget Constraints
   f. Information Start Time Constraints
   g. Detour Constraint

Constraints on Time-Dependent Network Flows

The network flow balance constraints are required for both static and time-expanded networks in order to represent flow propagation correctly. While flow balance constraints based on physical links are quite common in the literature, it is non-trivial to consider the flow balance in a space-time expanded network with user class transition (from HI to PI). In the proposed model, constraints (1) - (3) are flow balance constraints at origin, destination and intermediate nodes, respectively.

Flow balance constraints on origin node

At the origin node, each agent is loaded from his path origin node and the travel time from the origin to the first node is zero. Since no pre-trip information is considered in this study, all agents departing the origins follow the historically best route on the first link. Note that, set Ok represents the origin for each agent and each element contains three entries, origin node ID of physical network, agent ID, and departure time stamp. This is represented by the following equation:

$$\sum_{s}\sum_{j} y_{ijts}^{k} = 1, \quad \forall\ (i,k,t) \in O_k \tag{1}$$

Flow balance constraints on destination nodes

Next every agent will flow into destination nodes from one of the intermediate nodes at different times. We consider the possibility of the existence of information provision on this layer by allowing different user classes. Note that set D_k represents the origins for each agent and each element contains two entries, including destination node ID of physical network and agent ID. There is no time stamp entry compared with O_k since there is no set time for agent arrival because of complex conditions during the travel, such as incident, congestion, and diversions. This is represented as follows:

$$\sum_t \sum_s \sum_i [y^k_{ijts} + z^k_{ijts}] = 1, \quad \forall (j,k) \in D_k \tag{2}$$

<u>Flow balance constraints on intermediate node</u>

The intermediate nodes here are not necessarily on the historical path when considering the possibility of diversion. This constraint applies to every node on the layer other than origins and destinations for each agent. Also, waiting arcs (*i,i,t,t+1*) are allowed in the flow balance constraint for intermediate nodes (not for origins and destinations), to represent the condition where downstream link capacity is not enough for all incoming agents and queues build up. This is represented as follows:

$$\sum_t \sum_i [y^k_{ijts} + z^k_{ijts}] = \sum_{t'} \sum_{i'} [y^k_{ji'st'} + z^k_{ji'st'}], \quad \forall j \in IN, s \in T, k \in K \tag{3}$$

This constraint is also very crucial for modeling information provision. Intermediate nodes allow activity on them, which means information provision is realized at nodes. As seen in the example Figure A-13, two agents with historical information arrive at node *j* at time stamp *t*. Assuming they do not need to wait at node *j*, agent 1 continues on the historical route while agent 2 receives real-time information and is converted to en-route information agent (dashed line) and starts to use the suggested alternative route. Constraint 3 requires total volume constraint, but allows transfers of user information. In this way, the modeling of information provision is reflected by the conversion of network user groups at intermediate nodes.

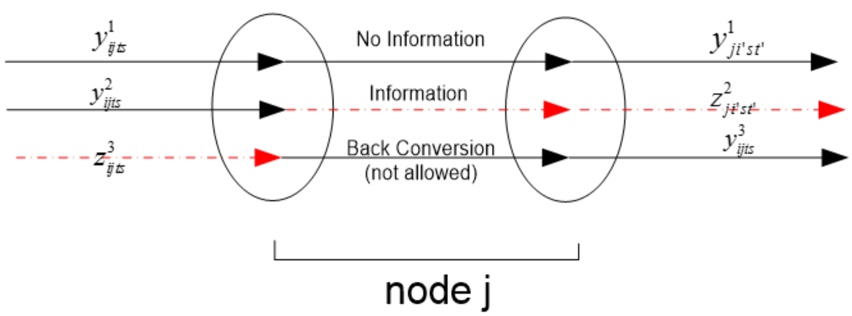


Figure A-13: Illustration of User Information Group Conversion Process [Source: Booz Allen]

Condition 1: For agents that have not received any information, z^k_{ijts} = 0, Eq. (3) reduces to:

$$\sum_t \sum_i y^k_{ijts} = \sum_{t'} \sum_{i'} y^k_{ji'st'}, \quad \forall\, j \in IN, s \in T, k \in K$$

Condition 2: At an information provision point (diversion point), Eq. (3) reduces to:

$$\sum_t \sum_i y^k_{ijts} = \sum_{t'} \sum_{i'} z^k_{ji'st'}, \quad \forall\, j \in IN, s \in T, k \in K$$

Condition 3: For already diverted flow. Eq. (3) reduces to:

$$\sum_{t}\sum_{i} z_{ijts}^{k} = \sum_{t'}\sum_{i'} z_{ji'st'}^{k}, \quad \forall j \in IN, s \in T, k \in K$$

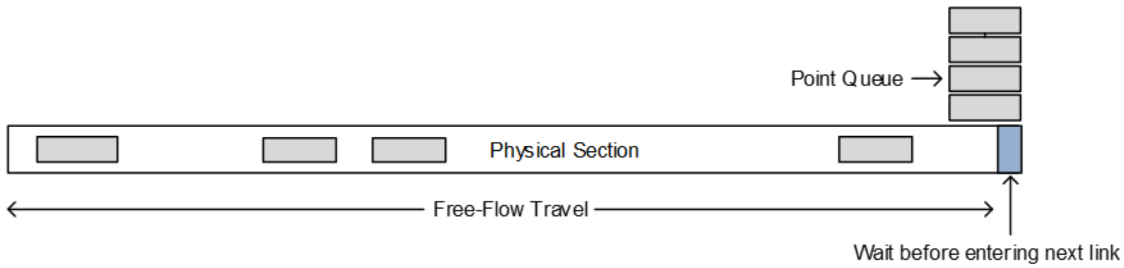


Figure A-14: Illustration of Point Queue Model [Source: Booz Allen]

Constraints on Network Propagation

The EnableATIS modeling, here, also adopts concepts of the bottleneck model (Vickery, 1963) for dynamic network flow propagation, as show in Figure A-14. In this model, agents always move along a link with the free flow speed until they arrive at the exit point, where they form a queue if the outflow rate (or inflow rate of next link) they induce exceeds the maximum value (capacity flow) of the link. Since the bottleneck model ignores the physical length of agents and assumes that a queue occupies a point, it is also known as the vertical queue or point queue (P-Q) model. Other dynamic network loading models can also be adopted in the optimization framework we proposed here with some modification, such as Newell's simplified kinetic wave model (Newell, 1993; Lu, 2013) and cell transmission model (Daganzo, 1994, 1995). However, using more complex models may add to the complexity of the optimization framework and increases computation burdens. In this project, link capacity is considered as inflow capacity, which means only a certain number of agents are allowed to enter the link at a time stamp, as shown in the following equation:

$$\sum_{k}\sum_{s} [y_{ijts}^{k} + z_{ijts}^{k}] \le cap_{ijt}, \quad \forall (\mathrm{i}, \mathrm{j}, \mathrm{t}) \in A \tag{4}$$

If EnableATIS is allowed and an agent has to wait at or before a diverting node, System Optimum (SO) mathematical models may produce results allowing agents to wait at earlier nodes (instead of bottleneck nodes) while there is still unused capacity of next link along the historical path. This may be problematic in some cases. One example is shown in Figure A-15.

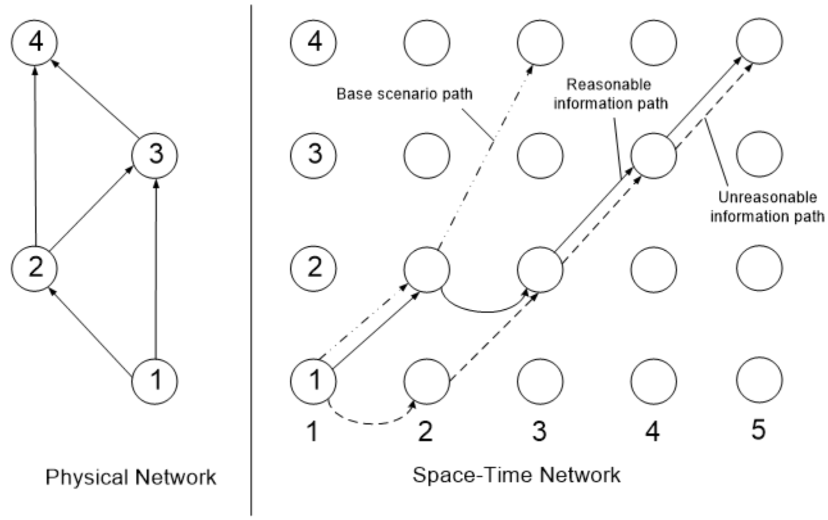


Figure A-15: Illustration of Continuous Flow Constraint [Source: Booz Allen]

An agent wanted to travel form node 1 to node 4 via path 1-2-4. The dot-dash line is the base case scenario path. When link (2, 4) is closed and information is provided only from time 3, the agent would wait at node 2 from time 2 to 3 (given the travel time of each link is 1) and then follow the suggested route 2-3-4. However, without extra constraints added, the program may let agent wait at node 1 from time 1 to 2 and then follow suggested route 1-2-3-4 without waiting in-between. This is not realistic since agents will travel along the historical path continuously and not stop unless no capacity is left in the next link. This becomes a problem if an agent stays on an earlier node too long, and the program may provide them information at that node, which is not possible in reality. Therefore, "continuous flow constraints" are added to prevent such unrealistic situations as shown in the following equations:

$$y^{k}_{jjs,s+1} \leq [\sum_{k'}\sum_{t}(y^{k'}_{jist} + z^{k'}_{jist})] / \text{cap}_{jis}, \forall (j,i,s) \in A, (i,j) \in H^{k} \quad (5)$$

where H^k is the historical link set of agent *k*. This means that, along the historical path, each agent must proceed unless there is not enough capacity ahead. Note that waiting arcs are not physical links and thus not included in set H^k.

It is known that mathematical formulations of system optimum (SO) problems are problematic in meeting First-In-First-Out requirements and in generating holding-back phenomenon. Generally, they would require the introduction of additional constraints that yields a non-convex constraint set, destroying many nice properties of the formulation and severely increasing the computational requirements. The EnableATIS mathematical model should be efficient in solving so that it can be used in real-time traffic management.

Constraints on EnableATIS Information

In addition to Equation 3, multiple other constraints are needed to model EnableATIS. Information activation constraints states that the diverted agents have already received real-time information and cannot be converted back to historical information again as shown below:

$$\sum_{i}\sum_{t} y^{k}_{ijts} \geq \sum_{i'}\sum_{t'} y^{k}_{ji'st'}, \quad \forall\ (i,s),(i',s) \in A,\ j \in IN, k \in K \quad (6)$$

Two other important constraints, historical information user constraint (Equation 7) and real time information provision constraint (Equation 8) decides where information can be located (candidate information locations).

Historical information provision constraints:

Historical information users will only use links that are historically used, with h_{ij}^k a pre-specified binary parameter. For example, as in the network in Figure A-11, a historical path of 1-2-4 for agent k can be represented by h_{12}^k =1 and h_{24}^k =1 while other h_{ij}^k =0. Thus, this constraint will force all y_{ijts}^k values except y_{12ts}^k and y_{24ts}^k equal zero. The historical links and h_{ij}^k value can be determined by many methods, such as GPS probe data or a traffic assignment equilibrium run.

$$y_{ijts}^k \le h_{ij}^k, \quad \forall (i, j, t, s) \in A, k \in K \tag{7}$$

Real time information provision constraints

Candidate information links that can be suggested to each agent/traveler via parameter g_{ij}^k is given by this constraint. On one hand, this parameter can be set by the TMCs to avoid traffic being diverted to unsuitable routes. One the other hand, this parameter can be set for each agent and make information provision more personalized. Without loss of generality, all g_{ij}^k values are set to be 1 for personalized traveler information. Note that g_{ij}^k is only for physical links and this is fully consistent with actual real-world conditions, where only physical paths can be suggested, though travelers who follow the suggested route might have different space-time trajectories.

$$z_{ijts}^k \le g_{ij}^k, \quad (i, j, t, s) \in A, k \in K \tag{8}$$

Information provision constraints

Information provision amount constraints (Equation 9) defines whether a certain agent *k* receives real time information at a certain node j and time stamp *s*.

$$r_{js}^k = \sum_t \sum_i [y_{ijts}^k] - \sum_{t'} \sum_{i'} [y_{ji'st'}^k], \quad \forall j \in IN, s \in T, k \in K \tag{9}$$

Node information provision constraints

Node information provision constraints (Equation 10) define the total number of agents that receive real time information at a certain node *j* and time stamp *s*. Note that x_{js} is also a variable in this formulation to control the number of agent that can receive information.

$$\sum_k r_{js}^k \le x_{js}, \quad \forall j \in IN, s \in T \tag{10}$$

Budget constraints

Information provision usually comes with a cost. Traditional VMS incurs a lot of infrastructure and maintenance investment. The proposed system requires capacities of commutation and user devices. Also, receiving and comprehending information (especially complex ones) is distraction to them and a type of invisible cost. Thus, we introduce a parameter B, information provision budget. Parameter α is the cost to provide information to each travelers. Parameter B should be decided based on available resources, engineering judgment, and sensitivity analysis. If we assume α equal to 1, the parameter B can also be considered total number of agents that receive real time information.

$$\alpha \cdot \sum_{j}\sum_{s} x_{js} \le B \tag{11}$$

Information start time constraints

Information start time constraint (Equation 12) states that information will only be provided after an incident is detected. This is achieved by restricting that all x_{js} is zero until incident detection time *ω*. This indicates that information is only provided when incident happens, such as a crash or severe congestion.

$$\sum_{j}\sum_{s \le \omega} x_{js} = 0 \tag{12}$$

Detour constraints

The system optimum solution has long been criticized because it may discriminate against some users in favor of others and sometimes recommending very long detours. From the perspective of user experience, this type of solution is unacceptable. Therefore, detour constraints are introduced to prevent long detours for every traveler. Jahn et al. (2005) proposed several different constraints of this type, such as the ones based on free-flow travel time or user equilibrium travel time. Here we constrain the detour travel time to no more than *(1+β)* time of the historical travel time, which can be obtained from real world probe data or results from dynamic network loading.

$$\sum_{i,j,t,s} c_{ijts} \cdot (y_{ijts}^{k} + z_{ijts}^{k}) \le (1+\beta) \cdot c_{hist}^{k} \quad \forall k \in K \tag{13}$$

Objective Function

The objective function is the total system cost, representing the total system travel time by all travelers in the system.

$$\mathrm{F(x,y,z)} = \sum_{i,j,t,s}\sum_{k}\left\{ c_{ijts} \times \left[y_{ijts}^{k} + z_{ijts}^{k} \right] \right\} \tag{14}$$

where $c_{ijts} = FFTT(i, j)$, free flow travel time from node *i* to node *j* from time t to time *s= t+FFTT(i,j)*;

$c_{i,i,t,t+1} = 1$ for waiting arcs at node *i* from time t to time *t+1*.

With the objective to minimize the objective function *F(x,y,z)*, total system cost, the optimization problem can be formulated as a mixed integer programming model, as in Eq. (15). Note we also add a binary variable constraint and nonnegative constraint of the decision variables at the end.

$$\min_{x,y,z} \sum_{i,j,t,s} \sum_{k} \left\{ c_{ijts} \times \left[y_{ijts}^{k} + z_{ijts}^{k} \right] \right\} \tag{15}$$

subject to:

Equations 1 through 13.

Heuristic Path-Finding Approach

The agent-based optimization model proposed above describes the problem analytically and captures complex flow balance relationships for travelers with different types of information. It is able to provide a global view for the problem to obtain a system optimum solution. However, analytical models like this usually suffer from their inability to solve large-scale problems. Therefore, a Lagrangian Relaxation-based heuristic approach is implemented in DTALite, for solving the agent-based optimization problem.

DTALite can spontaneously reflect the capacity constraints of this optimization problem. For example, the network flow balance constraints on origins, intermediate nodes, and destinations (Equations 1 through 3) and continuous flow constraint (Equation 5) are met automatically in a simulator. Also, as discussed earlier, the limit of a simulator is that agents only follow local rules without a global view and impact the system through their own behavior and interactions with other agents. It is difficult to ensure system improvements by considering only agents' local rules and behavior. Thus, for a traffic management application, it is of critical importance to introduce an optimization process to optimize critical values and achieve system optimum.

With EnableATIS, we can know the agent's historical routes, departure time, and the location of the agent when an incident is detected. In real applications, the agents' location can be obtained based on probe data such as GPS traces sent to the server by each agent. Since all other constraints can be easily met or handled in a simulation, the analytical optimization model can be reduced to the following form, as in Equation 16. As stated above, flow balance constraints (Equations 1 through 3) and continuous flow constraints (Equation 5) are met automatically in simulation. Information activation constraints (Equation 6) are also not necessary met since once one of a simulated agent's characteristics is changed, the characteristic will not be changed back unless otherwise forced to. Constraints such as historical information provision constraints (Equation 7) or real time information provision constraints (Equation 8) can be easily handled in a simulation by considering behavioral characteristics or local rules for each agent. Without loss of generality, budget constraints (Equation 11) are not considered. The detour constraints (Equation 13) can be checked every time when we find a new route for an agent. If the new route meets the constraint, accept it. Otherwise, stay with the original route.

Note that, for simplicity, we use only one variable y_{ijts}^{k} to indicate whether agent k uses link *(i,j)* from time stamp *t* to *s*. For the simulation implementation, the model reduces to:

$$\min_{y} \sum_{i,j,t,s} \sum_{k} \left\{ c_{ijts} \times y_{ijts}^{k} \right\}$$

subject to: (16)

$$\sum_{k} \sum_{s} y_{ijts}^{k} \le cap_{ijt}, \quad (i,j,t) \in A$$

$$y_{ijts}^{k} \in \{0,1\}$$

We dualize the capacity constraints (hard constraints) and the Lagrangian Relaxation reformulation of (Equation 16) is as follows:

$$\begin{aligned}\min_{y,\lambda} \quad \mathrm{L}(\mathrm{y},\lambda) &= \sum_{i,j,t,s}\sum_{k}(c_{ijts}\times y_{ijts}^{k})+\sum_{i,j,t}\lambda_{ijt}\left[\sum_{k}\sum_{s}(y_{ijts}^{k}-cap_{ijt})\right] \\ &= \sum_{i,j,t,s}\sum_{k}[(c_{ijts}+\lambda_{ijt})\cdot y_{ijts}^{k}]-KS\sum_{i,j,t}[\lambda_{ijt}\cdot cap_{ijt}]\end{aligned} \tag{17}$$

Subject to $y_{ijts}^{k}\in\{0,1\},\lambda_{ijt}\geq 0$

where λ is the Lagrangian multiplier, and K and S are the total number of agents/agents and potential link head node arrival time stamps. Equation is a Lagrangian relaxed problem and its optimal solution provides a lower bound to problem (16). Thus, solving problem Equation 17 involves the identification of optimal value λ that produces the tightest or largest lower bound to the primal problem Equation 16. The resulting problem is called a Lagrangian dual problem as shown below.

$$\max_{\lambda\geq 0} \quad \mathrm{L}^{D}(\lambda)=\inf\left\{\sum_{i,j,t,s}\sum_{k}(c_{ijts}\times y_{ijts}^{k})+\sum_{i,j,t}\lambda_{ijt}\left[\sum_{k}\sum_{s}(y_{ijts}^{k}-cap_{ijt})\right]\right\} \tag{18}$$

In this Lagrangian relaxation framework, in each outer loop iteration n, the solution procedure for Equation 16 consists of two major algorithmic steps: given a Lagrangian multiplier $\lambda^{(n)}$, find an optimal y value by solving the Lagrangian lower bound problem (Equation 19) and given y value and current network state, update the Lagrangian multiplier by using the subgradient optimization method which is discussed later.

$$\begin{aligned}&\min_{y} \quad \mathrm{L}(\mathrm{y})=\sum_{i,j,t,s}\sum_{k}[(c_{ijts}+\lambda_{ijt}^{(n)})\cdot y_{ijts}^{k}]-KS\sum_{i,j,t}[\lambda_{ijt}^{(n)}\cdot cap_{ijt}] \\ &\Leftrightarrow \min_{y} \quad \mathrm{L}(\mathrm{y})=\sum_{i,j,t,s}\sum_{k}[(c_{ijts}+\lambda_{ijt}^{(n)})\cdot y_{ijts}^{k}]\end{aligned} \tag{19}$$

subject to $y_{ijts}^{k}\in\{0,1\}$

In Equation 19, only links along the route taken by each agent k are considered. For each physical link *(i,j)*, the term c_{ijts} represents the link delay encountered by agent itself, with queuing considered by waiting arcs *(i,i,t,t+1)*. The term $\lambda_{ijt}^{(n)}$ can be considered as marginal delay to the whole system caused by the agent's arrival at an arc, either a physical link or a waiting arc. This insight is similar to those from many previous studies (e.g., Ghali and Smith, 1995). Then, the generalized time-dependent link cost for an agent arriving at link *(i,j)*, at time *t*, denoted by g_{ijt}, can be calculated by:

$$g_{ijt}=c_{ijts}+\lambda_{ijt}^{(n)} \tag{20}$$

Then generalized time-dependent path cost used by agent *k*, denoted by g_k, can be calculated by:

$$g_k = \sum_{i,j,t,s} (c_{ijts} + \lambda_{ijt}^{(n)}) \cdot y_{ijts}^k \tag{21}$$

Equations 19 through 21 can be further explained by borrowing the concept of link marginal delay of Ghali and Smith (1995), as in Figure A-16, where the agent arrival curve A(t) and agent departure curve D(t) is the traffic condition at the end of a link and insufficient downstream link capacity make this point a bottleneck. At time t_2, the agent arrival rate is greater than departure rate and a queue forms. When the one unit of agent arrives at time t_2, the queue length is q and he will be able to departure at time t_2, and the total link delay he would encounter is $d = t_3 - t_2$. However, the arrival of this agent also caused delay for other agents arriving here from time t_2 to t_4 (queue dissipation time), and the additional delay imposed on others is $t_4 - t_3$, which is similar to the concept of $\lambda_{ijt}^{(n)}$ in our model. Equation 19 means that for each agent, $\sum_{i,j,t,s} [(c_{ijts} + \lambda_{ijt}^{(n)}) \cdot y_{ijts}^k]$ is the path cost for this system optimum problem and the total for each agent should be minimized.

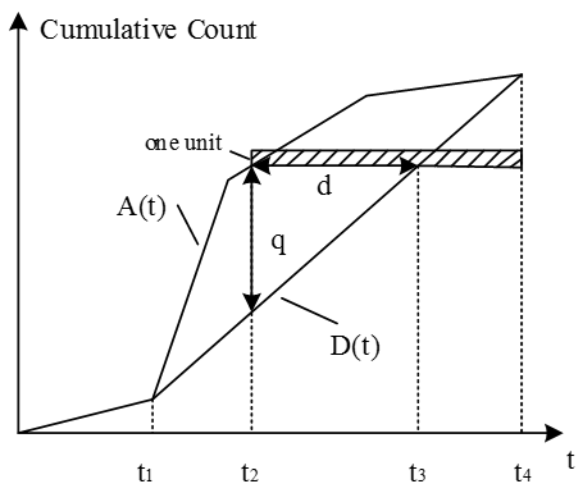


Figure A-16: Illustration of Concepts of Link and Path Marginal Delay [Adapted from Ghali and Smith (1995)]

Based on Bellman's principle of optimality, some modified label correcting algorithms (e.g., Ziliaskopoulos and Mahmassani, 1992) can be adopted to search for optimal time dependent least cost path for Equation 19. In the searching procedure, an *M*+1-dimensional vector-based label, denoted by $\Gamma_j = (\eta_j(t_0), \eta_j(t_0 + \sigma), \cdots, \eta_j(t_0 + \mathrm{M}\sigma))$, can be used to show the least travel cost from origin O to current node j at each time stamp $t' \in T$, where $\eta_j(t')$ is computed by $t' = t + c_{ijts}$:

$$\eta_j(t') = \begin{cases} \min\{\eta_j(t'), g_{ijt} + \eta_j(t)\}, & j \in N \setminus i, t' \in T \\ 0 & , j \in O, t' \in T \end{cases} \tag{22}$$

Note that in Ghali and Smith (1995), the marginal delay of a link or path is calculated using the realized network condition, while we use updated Lagrangian Multiplier in each iteration.

Heuristic descent direction method: Since each agent is considered in calculating the shortest path, significant system performance deterioration might be encountered if all agents searched for a route representing lower generalized cost. It is necessary to make sure the decent direction to avoid over-diverting agents in each iteration. Ghali and Smith (1995) presented a simulation-based approach to evaluate local link marginal travel time or delay on a congested link, based on cumulative flow curves. This Algorithm DEC was used in simulating EnableATIS.

Algorithm DEC:

Step 1: Obtain historical routes, departure time, and real-time location at the time of incident detection for each agent.

For each agent, do Step 2 and Step 3.

Step 2: Determine the agent new route with smallest marginal delay, calculated by summing the local marginal delay of each link on the route.

Step 3: If a new route is found in Step 2, determine the new value of total system travel time and accept the new route if it reduces total system travel time. Retain old route for the agent if total travel is not reduced.

Step 4: If new routes for agents are found in Step 2 and Step 3, then go to Step 2 and Step 3 for another iteration. Otherwise, terminate.

Sub-gradient method: The Lagrangian relaxation model (Equation 17) provides a lower bound for the primal problem. We adopt a sub-gradient method to update the Lagrangian multipliers λ iteratively. We want the lower bound as close to optimal value as possible, while the Lagrangian dual problem (Equation 18) needs to be solved. Meanwhile, the upper bound will be updated using newly available, better feasible path solutions (with a lower objective function value of problem (Equation 16)) to minimize the dual gap.

To iteratively update the Lagrangian multipliers λ for reaching tighter lower bounds, at each iteration, the direction of update can be calculated as:

$$\nabla \mathrm{L}_{\lambda_{ijt}}(\lambda) = \sum_{k}\sum_{s}(y_{ijts}^{k} - cap_{ijt}) \quad (23)$$

Then, the following equation can be used to update the Lagrangian multiplier λ_{ijt} for iteration n+1.

$$\lambda_{ijt}^{n+1} = \lambda_{ijt}^{n} + \theta_n \left[\sum_{k}\sum_{s}(y_{ijts}^{k} - cap_{ijt}) \right] \quad (24)$$

where the parameter θ_n is the step size for updating Lagrangian multiplier. There are multiple ways of determine the step size. Usually in optimization theory, an upper bound will be calculated at each iteration and then used to update step size. However, since evaluating the upper bound is expensive in a simulator, the heuristic approach adopts a moving average method for updating the step size, as below:

$$\theta_n = 1/(n+1) \quad (25)$$

Once the objective function of Lagrangian Relaxation reformulation problem (Eq. 17) between two consecutive iterations are less than a pre-determined error ε, or when the iteration number reaches a pre-specified maximum number $N_{\max}$, the algorithm is terminated.

Solution algorithm: As illustrated in Figure A-17, we now present the complete solution procedure as follows:

Step 1: (Initialization) Set n =0; Perform dynamic network loading using DTALite with initial path of each agent; initialize the Lagrangian multiplier $\lambda^{(n)}$, evaluate the objective function value $L^{(n)}$ of Lagrangian Relaxation problem (17). Go to Step 2.

Step 2: (Solve the relaxed model) Given Lagrangian multiplier $\lambda^{(n)}$ and current results from network loading, solve the problem (19) using a modified label correcting algorithm for time dependent least cost path problem, and Algorithm DEC, to find current optimal value for vector y.

Update the objective function value $L^{(n)}$ of Lagrangian Relaxation problem (17).

Go to Step 3.

Step 3: (Convergence checking) If $L^{(n)} - L^{(n-1)} < \varepsilon$ or $n > N_{\max}$, terminate the iteration and output current solution of vector y. Otherwise, go to step 4.

Step 4: Compute subgradient with Eq. (22) and update Lagrangian multiplier using Eq. (23). Go to step 2.

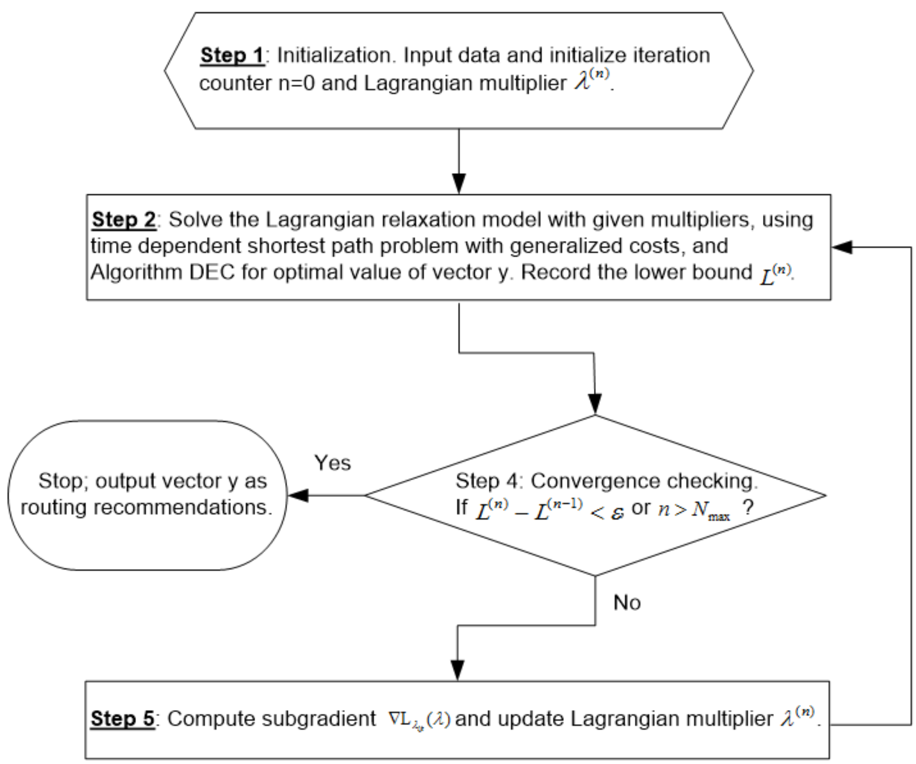


Figure A-17: Solution Procedure for Lagrangian Relaxation-Based Heuristics [Source: Booz Allen]

Appendix G. FRATIS Modeling Details

FRATIS consists of three different applications that are freight-related:

1. **DR-OPT** combine container load matching and freight information exchange systems to fully optimize drayage operations using powerful algorithms to leverage data from multiple sources.
2. **F-ATIS** and **F-DRG** are modeled as a single application called Freight Specific Dynamic Travel Planning and Performance. It includes all of the traveler information, dynamic routing, and performance monitoring elements that freight-truck user's need in one application and leverages existing data in the public domain, as well as emerging private sector applications.

FRATIS is, in essence, a special ATIS system for logistics and it shares many similarities of EnableATIS. However, the major focuses of FRATIS are different from the EnableATIS. For example, in addition to benefiting trucks everywhere via dynamic routing suggestions, FRATIS may be especially beneficial to trucks via proper scheduling at certain locations, such as ports, terminals, or borders. Another major difference between FRATIS and EnableATIS, more importantly, is the number of destinations. General travelers typically plan one destination per trip whereas the truck drivers most likely need to plan multiple destinations upfront to deliver or pick up goods. There are two types of FRATIS applications, long-haul freight transportation system in which routing guidance is performed across cities or even states; and multi-destination drop-offs and pick-ups (such as grocery store chains) within metropolitan areas. Figure A-18 demonstrates the high-level diagram of the prototyped FRATIS application under DMA Programs Prototype Development Project.

Mathematically, the route guidance problem for trucks can be viewed as a special version of the vehicle routing problems. In particular, during a truck trip, the truck needs to decide a proper sequence to visit those locations. Solving Vehicle Routing Problems (VRP) is typically very difficult when problems become large-scale and therefore a fast heuristic algorithm based on finding the minimum total cost for all possible visiting sequences is developed in FRATIS to provide guidance for trucks. The origin and destination, departure and arriving time window from origin and for each destination for each truck, the sketched road network with link travel time information and evaluation benchmark such as total travel time should be given to the algorithm as an input.

AMS Team has acquired the final version of the DFW and LA versions from the Open Source Portal. The application uses C# development environment with six different external dependencies and use of proprietary software. The FRATIS Bundle is being prototyped in California, Florida, and Texas. However, the acquired algorithm is difficult to use within a simulation context due to its external dependencies. The AMS team, understanding the significance of the application, has developed an independent version of the FRATIS application for use within the Phoenix testbed. For the Phoenix testbed, freight will be treated as a vehicle fleet with specific freight loading and routing attributes. Each vehicle (trucks) in the fleet will have its traffic flow properties. Furthermore, the origin and destinations, with timing attributes will be provided externally. The only way this fleet will interact with the rest of the vehicles in the network is that part of the network will be used by both trucks for freight and passenger vehicles and as such they will experience the same congestion and travel times.

As far as Phoenix testbed is concerned, the FRATIS bundle was represented by Freight Dynamic Travel Planning and Performance application. The team built algorithms to determine optimal visiting sequences of destination for trucks with multiple destinations as shown in Figure A-19. The application also enables recalculating these sequences and routes according to updated travel-times throughout the simulation.

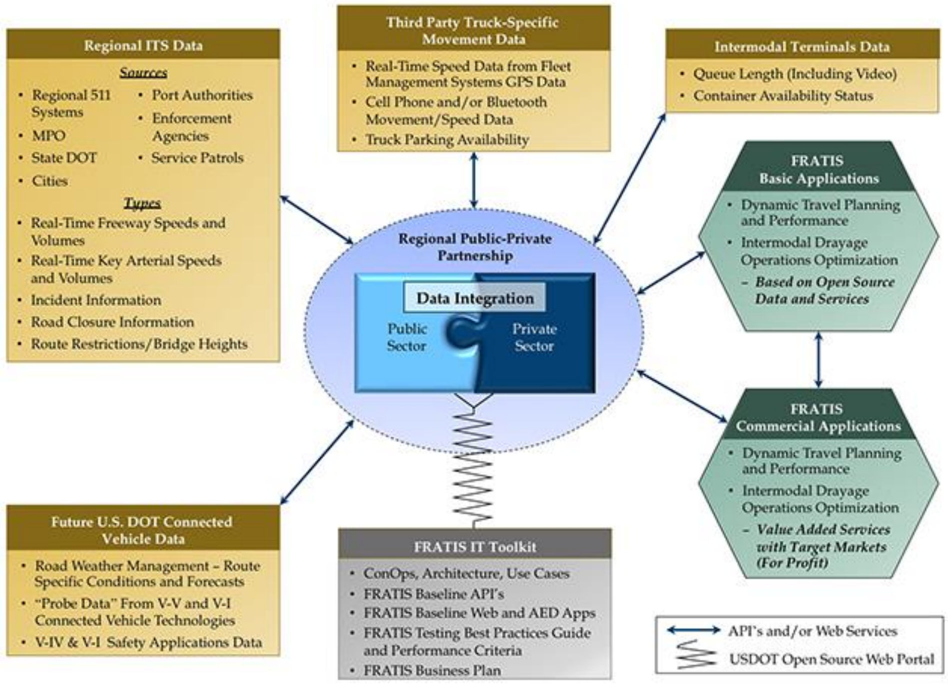


Figure A-18: Proposed High-Level System Concept for FRATIS Application[47] [Source: Booz Allen]

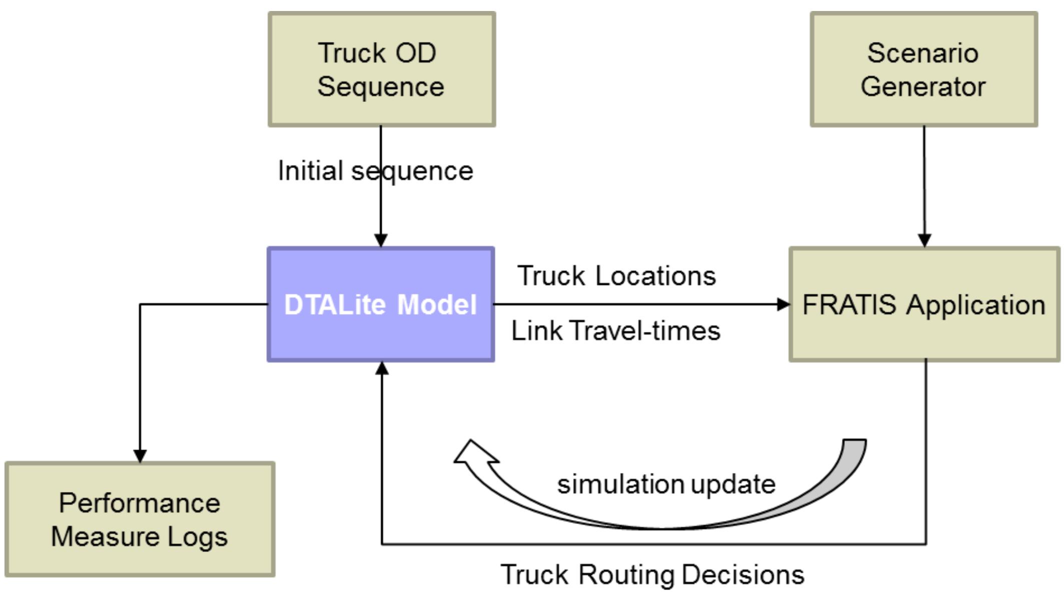


Figure A-19: Modeling of FRATIS Application [Source: Booz Allen]

FRATIS in the Phoenix Testbed

FRATIS is in essence a special ATIS system for logistics and it shares many similarities of EnableATIS. However, the major focuses of FRATIS are different from the EnableATIS. For example, in addition to

[47] http://www.its.dot.gov/dma/dma_development.htm

benefiting trucks everywhere via dynamic routing suggestions, FRATIS may be especially beneficial to trucks via proper scheduling at certain locations, such as ports, terminals, or borders. Another major difference between FRATIS and EnableATIS, more importantly, is the number of destinations. General travelers typically plan one destination per trip whereas the truck drivers most likely need to plan multiple destinations upfront to deliver or pick up goods. There are two types of FRATIS applications, long-haul freight transportation system in which routing guidance is performed across cities or even states; and multi-destination drop-offs and pick-ups (such as grocery store chains) within metropolitan areas. Considering the network topology of the Phoenix AMS testbed (more specifically, the City of Tempe) and the power of available tools, the ASU team decided to focus on evaluating an important condition as follows:

Assume a truck driver has multiple destinations to visit for goods deliveries and pickups. The dispatcher will need to determine the sequence of destinations as well as the routes to minimize the total travel cost, such as travel time. Prior to FRATIS deployment, the driver primarily plans his trip based on his experiences, or the historical travel times. However, the historical travel times are often not reliable because of the non-recurrent incidents on roads as well as other random factors. As a result, this truck driver often experienced substantial delays to finish his travel plan. Thanks to FRATIS, now the truck travel can plan his multi-destination trip based on the latest traffic condition and possible bottlenecks on the road. Before he departs, the FRATIS can provide the sequence of destinations to visit as well as recommend routes. In the meantime, the FRATIS may also warn the truck of bottlenecks down the route and recommend alternative route according to the real-time travel times. As result, the truck driver will substantially reduce the total travel cost.

To evaluate the above condition, the ASU project team divided the task into several sub tasks:

1. Develop algorithms to determine the optimal visiting sequences of destinations;
2. Run the HD-DTA model multiple times to reach the initial user-equilibrium condition which is considered the initial historical traffic conditions;
3. Based on certain simple rules, such as “always visit the closest destination” and the historical condition, determine the usual visiting sequences of destinations and the reasonable routes;
4. Introduce bottlenecks in the HD-DTA network to reflect the non-recurrent events. As a result, the new traffic pattern will be different from the historical one;
5. Following the same visiting sequence and path as formed in Step 2, calculate the total travel delay for a truck;
6. Use the algorithm developed in Step 1 and recalculate the visiting sequence and proper routes based on the new travel time in Step 4 and then calculate the total travel delay;
7. Compare the results out of Step 5 and Step 6 and then evaluate the benefits.

Please note that this algorithm may not be reflective of the FRATIS system envisioned by the DMA Program. For a comparison with the DMA prototype and system design, please refer to Section 2.7. Given the lack of data source for this experiment, the AMS team decided to arbitrarily select origins and destinations.

Simulation Platform for FRATIS

To evaluate the benefits of FRATIS, the testbed needs to simulate two traffic conditions: (1) historical traffic condition in which truck drivers will form their experiences to determine departure time and visiting sequence of multiple locations during a trip from day-to-day learning. The DTA network will be simulated multiple times until the dynamic user equilibrium is reached; (2) traffic condition with non-recurrent bottlenecks in which truck link travel times will be dynamically changed. Figure A-20 shows a demonstration how and where to create bottlenecks in the Phoenix testbed for Scenario I. The corresponding bottlenecks will be simulated in the other three scenarios.

Without FRATIS, truck drivers are supposed not aware of the bottlenecks down the road. As a result, they will stick with their origin plan and run into congestions and may not finish their delivery missions in time. In contrast, thanks to FRATIS, truck drivers will be able to reschedule their routes and visiting sequences according to the latest link travel times to avoid congestions.

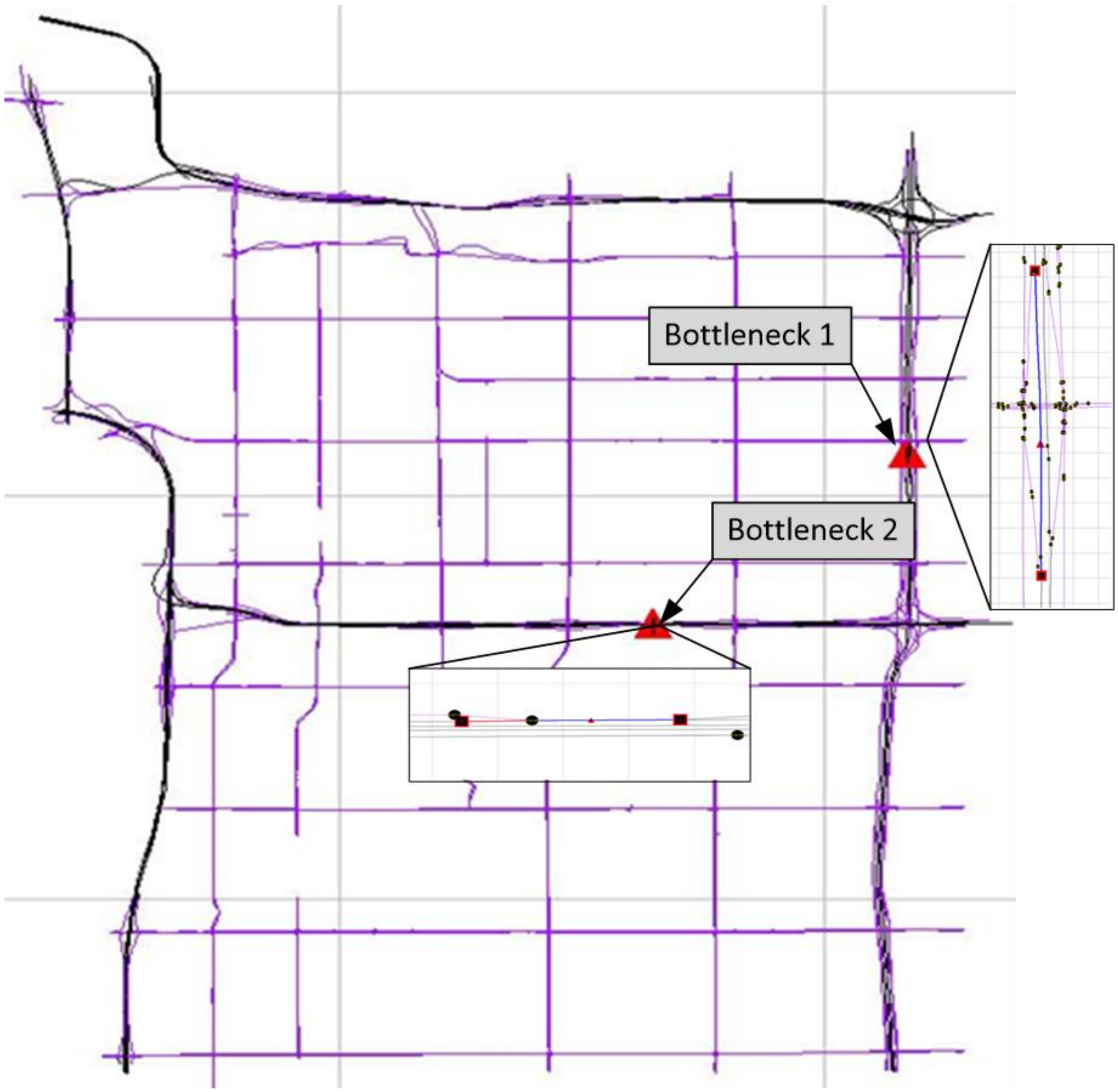


Figure A-20: Locations of Non-Recurrent Bottlenecks in Tempe [Source: Booz Allen]

FRATIS Algorithm Development

Mathematically, the route guidance problem for trucks can be viewed as a special version of the vehicle routing problems. In particular, during a truck trip, the truck needs to decide a proper sequence to visit those locations. Solving VRP problems exactly is typically very difficult when problems become large-scale and therefore the ASU protect team decided to develop a fast heuristic algorithm to provide guidance for trucks.

Required inputs:

For each truck, the following inputs are necessary to determine its trip route:

1. Origin and destination(s)
2. Sketched road networks with link travel time information
3. Departure time window;
4. Arriving time windows at each destination;
5. Benchmarks for evaluation, such as total travel time

Algorithm description:

1. Identify the requested time windows and distance of the truck from origin to multiple locations. This is shown in Figure A-21.

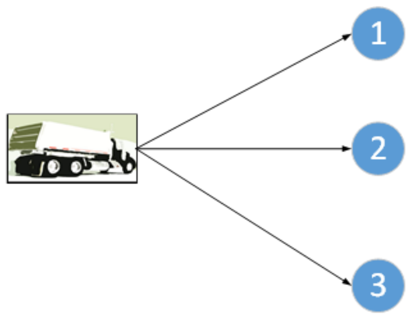


Figure A-21: First Step of FRATIS Algorithm [Source: Booz Allen]

2. Identify all feasible visiting sequence of the destinations. As shown in Figure A-22, if five destinations need to be visited by Truck 1, we will first identify all the possible visiting sequence Calculate the cost for all possible visiting sequences and find the minimum cost and the corresponding visiting sequence. This cost represents the aggregated link-travel times to achieve the visiting sequence. Note some visiting sequences (as illustrated in red in Figure A-22) may not be feasible for violating some constraints. After scan all the feasible visiting sequence. Truck drivers will trip according to this sequence and achieve the minimal travel time. If necessary, the truck drivers may ignore certain locations to maximize the possible deliveries.

Changes Brought by FRATIS:

Prior to the deployment of FRATIS, truck drivers primarily determined the visiting sequence according to their experiences, which can be viewed as based on the historical traffic conditions. However, if some non-recurrent (i.e., unexpected) bottlenecks occur along their proposed paths, trucks may run into congestion at certain locations and the delay will propagate and affect all the subsequent locations. After FRATIS is deployed, truck drivers can be aware of the real-time traffic conditions and get routing suggestions. As a result, the number of feasible visiting sequences may be change to avoid congestions.

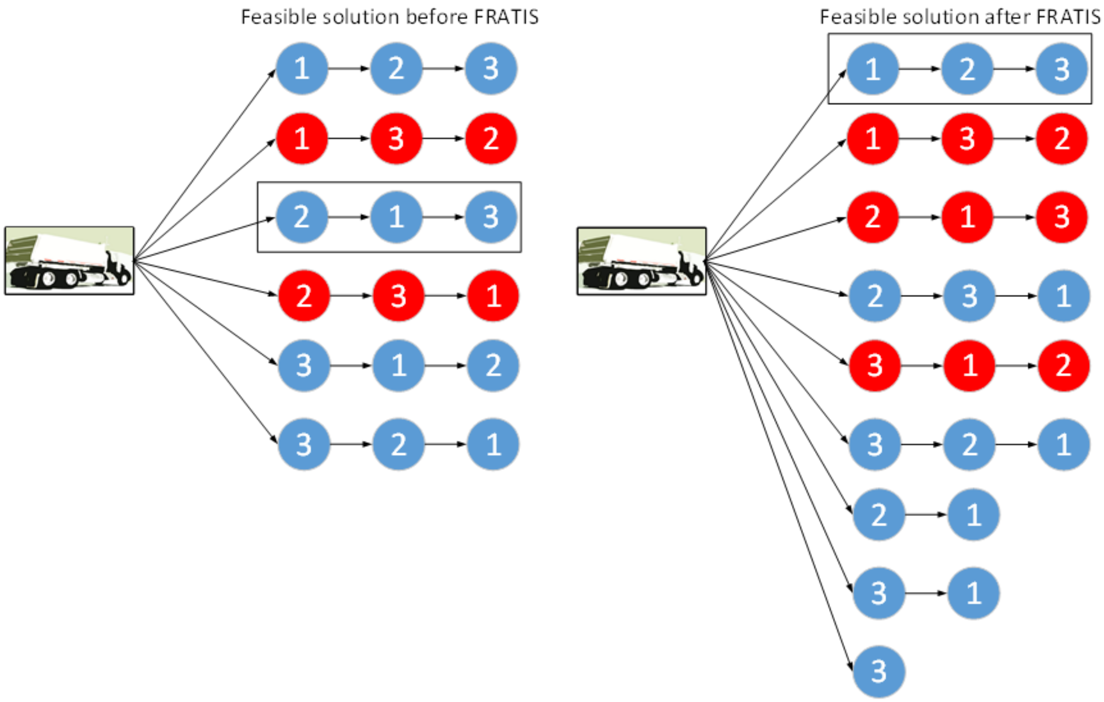


Figure A-22: Second Step of FRATIS Algorithm [Source: Booz Allen]

Appendix H. IDTO Modeling Details

IDTO consists of three different applications:

1. **T-CONNECT** aims to improve rider satisfaction and reduce expected trip time for multimodal travelers by protecting transfers between both transit and non-transit mode and facilitating coordination between multiple agencies.
2. **T-DISP** aims at advancing demand-responsive transportation services using existing technology systems and expanding transportation options. It seeks to match travelers' requests for trips with available transportation providers' services.
3. **D-RIDE** is a car-pooling system that provides drivers and riders with the flexibility of making real-time transportation decisions and aims at increasing the use of non-transit ride-sharing options including carpooling and vanpooling and improving the accuracy of vehicle capacity detection).

The IDTO Bundle is being prototyped as a mobile device application in Columbus, OH and Central Florida by Battelle. T-CONNECT and T-DISP applications are prototyped together as a single mobile device application "Connect and Ride". ZimRide, a proprietary ride-share application was used for prototype testing of D-RIDE functionalities. The Booz Allen Team evaluated functionalities of the T-CONNECT application and due to the extended scope of work it would require for integration, it was not evaluated in the AMS project. T-CONNECT simulation requires assigning passengers in vehicles (including transit vehicles) in the simulation model and holding buses and transit vehicles to make a connection after a request to hold is acknowledged and accepted. This requires significant additional features not available in current simulation testbeds. Currently, passengers/people in the Phoenix testbed appear only in the decision-making activity of selecting a start time and a route. After that the simulated entity is a vehicle with a given number of passengers.

The Booz Allen team has reviewed the system design and architecture documentation for the T-DISP application and developed some of the T-DISP functionalities into the Phoenix testbed model. When the demand responsive schedule for bus/transit is available to the simulation testbed, the simulated traveler will be either picked-up at origin at the scheduled time, or the simulated vehicle with traveler will be directed to the bus/transit stop. The testbed will provide the T-DISP application the passengers' predicted arrival times. Some D-RIDE application functionalities would be modeled in the Phoenix testbed. D-RIDE application requires recording passengers' waiting, picking-up, dropping-off status and the vehicle-to-passenger paring process in the simulation model. When the vehicle-to-passenger assignment and routing schedule are available to an enhanced simulation model, the traveler will be either picked-up at origin at the scheduled time, or the vehicle with passengers will be routed through externally specified data interfaces from the ride-share application. The testbed will provide predicted and simulated trip times of different routes used by vehicles with passengers to the D-RIDE application.

T-DISP Application

The underlying algorithm of the T-DISP application is to find the most appropriate transit path for passengers from their origins to their destinations. Compared to the standard shortest path finding algorithms, the uniqueness of transit path finding algorithm is that the algorithm needs to not only determine a non-stop transit path for passengers but also consider possible transferring (i.e., waiting) from one line to another line at some transit stops under certain conditions to avoid congestions and improve travel time reliability.

Given that nearly all the transit routes are on arterials in Phoenix while the collected incident data are on freeways, some arbitrary assumptions must be made. It is necessary to select the most representative transit routes, the number of passengers, origin-destination pairs. All these considerations are to ensure that, from the origin, there are a few interchangeable bus lines at certain stops and appropriate demand from the origin to the destination. To reflect four various scenarios, the corresponding link travel times were modified to match the results of EnableATIS evaluation. The baseline scenario will be that all passengers form his own route choice based on historical (day-to-day) riding experiences. In the slang of traffic simulation, it is called user equilibrium. Specifically, passengers will all try to take the bus with the shortest travel time. However, due to the capacity of buses, many passengers cannot take the immediately arriving bus but have to wait for the next one. As a result, the total bus travel time (moving and waiting) may be longer to most passengers and they may decide to take alternative routes along which even the total moving time is longer but the total travel time (moving plus waiting) may be shorter compared with the first option. Passengers will continue learning and changing their routes until no further travel time shortening can be achieved. In that case, the transit user equilibrium is reached. However, in reality such equilibrium can be easily broken due to non-recurrent incidents along routes, such as road blocking due to car accidents. In that case, the transit control center should quickly determine a new solution in response to such changes and notify passengers to change their routes to avoid delays. Through examples, the evaluation in this report focuses on answering questions like whether the proposed T-DISP algorithm can benefit the passengers and, if so, to what degree.

To evaluate the above condition, the ASU project team divided the task into several sub tasks:

1. Develop algorithms to determine the shortest travel options for travelers including both bus routes and transferring bus stops;
2. Based on the experienced travel times in EnableATIS, selected origin and destination pairs, the number of passengers and selected bus routes, run the PHX transit network multiple times to reach the initial transit-user-equilibrium condition which is considered the historical conditions before T-DISP;
3. Introduce bottlenecks in the transit network to reflect the non-recurrent events. As a result, the new traffic pattern will be different from the historical one;
4. Following the same visiting sequence and path as formed in Step 2, calculate the total travel delay for a truck;
5. Use the algorithm developed in Step 1 and recalculate the routes for passengers
6. Adjust dispatching schedule according to users' response (10 percent, 30 percent, 50 percent, 80 percent)
7. Compare the results out of Step 5 and Step 6 and then evaluate the benefits.

There are two steps in developing the Phoenix transit network based on Google Transit Feed. According to the Google Transit Feed data, the related data include transit routes data in which the ID, destination and type of each route are described; the shape file in which the geographical coordinates of each transit line are provided; the stops file in which the geographical coordinates of each transit stop are provided; and the stop times at each stops. As such, the first step is to visualize all transit lines and stops in Phoenix as shown in Figure A-23.

Given that the geographical coordinates in Phoenix transit network and previously created HD-DTA network are not exactly the same because they were extracted from different data sources, it is also necessary to conduct a map matching in the HD-DTA network to identify the list of links that each transit lines are composed of. Figure A-24 demonstrates the map matching results to map the transit lines into the HD-DTA network. After the above steps, all the transit lines (including the light rail) passing the City of Tempe are identified and their corresponding link IDs in the HD-DTA network can be identified. Since four scenarios have been extensively evaluated for EnableATIS, the experienced link travel times in four scenarios will be used to represent the background traffic under which the proposed T-DISP may provide different solutions to passengers.

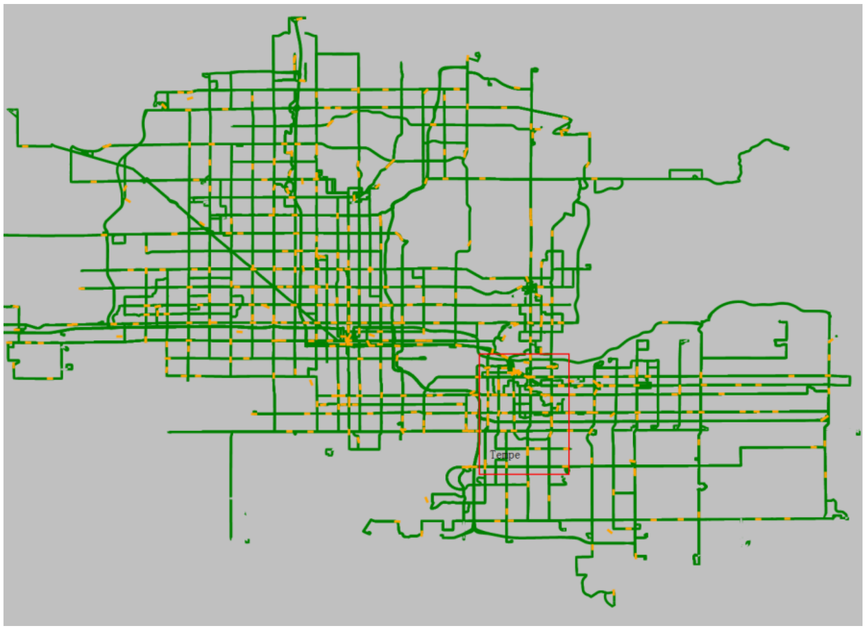


Figure A-23: Transit Network in Phoenix [Source: Google Transit Feed]

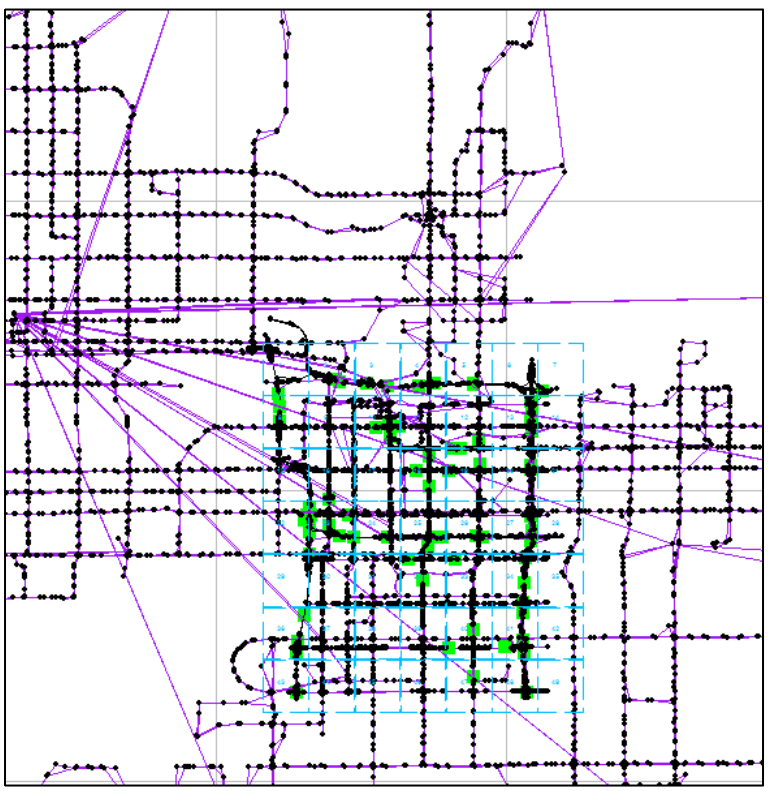


Figure A-24: Map-Matching Phoenix Transit Network to HD-DTA Network [Source: ASU]

Methodology

In a transit network, passengers will dynamically choose routes (transit lines) according to the transit schedule and locations of transit stations. Each transit vehicle has its storage (ridership) capacity. For example, in peak hours, if too many passengers choose the same transit line, congestion will occur in the station, and people who are not able to get on the bus should queue and wait for the next bus or transfer to another transit line.

An example is illustrated to describe the passengers' transit route choice behavior. There are two transit lines, one line (L1) is from station A to station E, and the other line (L2) is from station D to station E. Vehicles #1, 2, 3 belong to line L1, and vehicle #S1 belongs to line L2. Assume all the transit demands are from station A to station E. For one passenger who desires to departure at time t1, the best (fastest) way is to take on the bus #1 (line L1) to destination E without any transfer. If the vehicle #1 is overloaded, the passenger will not able to take on the bus. He/she has to wait for the next bus (bus #2, Line 1). A better choice is to transfer to line L2 and take on the bus #S1. He/she may reach the destination E much earlier than taking on bus #2. If unfortunately, the bus #2 and bus #S1 are also overloaded, the passenger has to wait for the bus #3. The waiting time will be long, and the passenger may postpone its departure time to reduce the waiting time. Figure A-25 illustrates the need for the algorithm to calculate transferring-allowed shortest transit paths for individual passengers. This problem is also known as transit assignment problem.

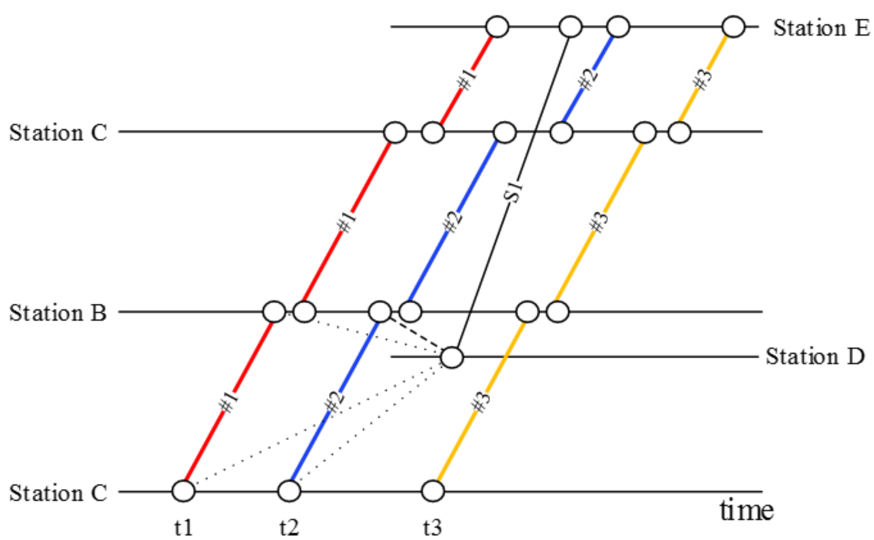


Figure A-25: Illustration of Transfer at Transit Stops [Source: Booz Allen]

The transit assignment problem is to find a system optimal solution to reduce all passengers' travel time, or find a user-centered optimal solution to minimize each passenger's travel time. Passenger will dynamically find a faster route among accessible transit lines to reach his/her destination as soon as possible. Different with traditional traffic assignment problem, transit schedule and transit lines should be taken into consideration. Two situations will be detailed discussed to calculate the time-dependent travel time,

1. Transfer right at the same station
2. Transfer between different stations

In an intermodal urban road network, there are several trip modes, such as transit (bus, BRT, subway), driving (private car, HOV, truck with different PCE), and combined mode (Park & Ride). Different types of users travel in a multi-layer network with road and vehicle capacity constraints, and they are interrelated and interact on each other.

For the transit assignment simulation, it is needed to build an intermodal dynamic traffic assignment model which is composed of two major components, namely shortest path finding and dynamic network loading, to describe the complex dynamic travel characteristics in an intermodal network. In such a new model, the transit schedule is considered to find a time-dependent shortest path in a transit service network, and the tasks of picking-up and dropping-off passengers need to be systematically modeled in the stage of multi-modal dynamic network loading.

There are a number of challenges in developing the intermodal model, including, how to precisely record an agent's space-time trajectory with bus boarding and delighting events, how to enable a paralleling computing mechanism to boost the simulation speed in a large regional network and how to find a shortest path considering the transit timetable and transfer time between different lines.

To describe the complicated situation that different users are travelling in the intermodal network, a physical link should be modeled as several copies (in terms of logical links) for its different users. For example, Figure A-26 includes 13 nodes, with three different types of facilities, with three different types of users, namely driving only, park and ride (P&R) and transit users. In particular, driving users travel in the routes with red line (1->2->4->10->12, 1->3->5->11->12), BRT users travel the route with green line (1->6->7->13->12), P&R users travel in the (1->2->4->8->7->13->12, 1->3->5->9->7->13->12).

In the enhanced DTALite model, we added a new attribute for each link namely "demand_type_code". A BRT link in Figure 2-2 is allowed for BRT users or transit passengers only, and a driving link is allowed for both buses and private cars. The single network is then extended to a multi-layer network and on each layer is a sub-network that the corresponding types of users are allowed to travel. For example, a BRT vehicle or a BRT passenger travels on a BRT layer.

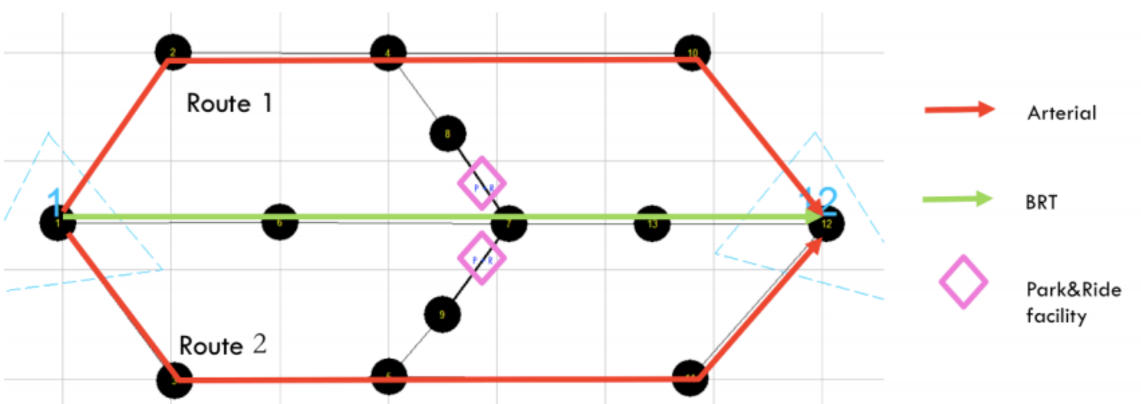


Figure A-26: Three-Corridor Intermodal Network with Three Facilities [Source: ASU]

Modeling Details

A service node can be seen as a transit station, and it will connect transit link and walk link only. Walk-in link will lead to pick up list, drop off list will lead to pick up list or walk-out link. Transit-in link will lead to vehicle list, and then lead to transit-out link. This is shown in Figure A-27.

1. Passengers from vehicle list to drop off list. (get off)
2. Passengers from drop off list to pick up list. (transfer)
3. Passengers from pick up list to vehicle list. (get on)

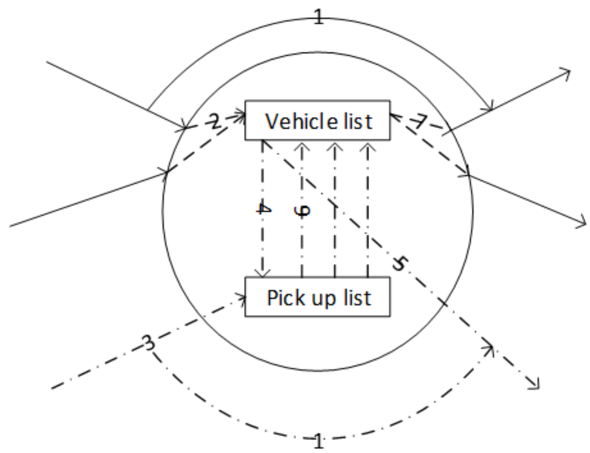


Figure A-27: Dynamic Network Loading Process on a Service Node [Source: Booz Allen]

The step-by-step process for transit vehicle/ passenger movement in a network is listed below:

1. A private car moves from the exit queue of the incoming link to entrance queue of the outgoing link. (Agent does not enter the service node)
2. A transit car moves from the exit queue of the incoming link to vehicle list of the service node. (Transit car enters the service node)
3. A passenger moves from exit queue of incoming link (for pedestrian walking) to pick up list. (Pedestrian enters the service node, walks to station and wait for a bus)
4. A passenger moves from vehicle list to pick up list. (Pedestrian gets off the bus and transfers to another transit line)
5. A passenger moves from the vehicle list to entrance queue of outgoing link (Pedestrian gets off a bus and walk out of the service node)
6. A passenger moves from the pick-up list to vehicle list. (Pedestrian gets on the bus)
7. A transit car moves from the vehicle list of the service node to entrance queue of the outgoing link. (Transit vehicle leaves the service node)

Example Model

Three demand types are deployed in the 3-corricor tutorial network (Figure A-26), which includes driving alone, transit (BRT), and Park & Ride. The initial demand for each demand type is 1000 vehicles per hours. In the following analysis process, demand will be changed according to different scenarios.

Driving Alone Demand Impact

The purpose is to test how high and low levels of passenger car demand are affect the transit and Park& Ride travel model in terms of travel time. As illustrated in Table A-3, low drive alone demand - 1000 vehicles per hour and high drive alone demand - 2000 vehicles per hour are tested using the intermodal network. After achieving user equilibrium by 20 iteration simulation processes, the results are showed below:

Table A-3: Driving Alone Impact on Demand

	Base Demand	Increased Demand
Drive Alone	1000	2000
Park and Ride	1000	1000
Transit	1000	1000

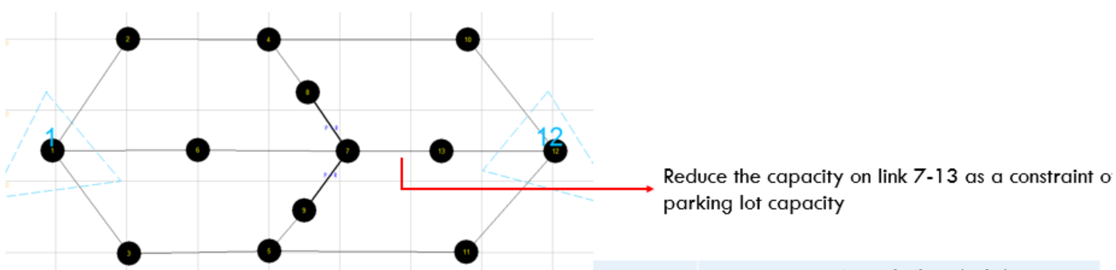
The results illustrate that under low drive alone demand, Park& Ride riders tend to choose shorter free flow travel time route 1, contrasts with under high drive alone demand, they have to shift 25 percent to route 2, which has longer travel time. This is the illustration that the intermodal network showing the driving mode has impact on public transit mode choice and travel behaviors:

demand	Base_demand (vehicle/hr)			High DA demand(vehicle/hr)		
Drive alone	1000			2000		
P&R	1000			1000		
	Assignment results_vehicle/hr					
	Route 1	28	2.8%	Route 1	294	29.4%
	Route 2	972	97.2%	Route 2	706	70.6%

Figure A-28: Drive Alone and Park & Ride Demand [Source: Booz Allen]

Parking Lot Capacity

In Nexta, the parking lot capacity can be reflected by changing the related link capacity. So in this study, we reduce the capacity on link 7-13 as a constraint of parking lot capacity, test on the same demand using base parking lot capacity and 1/3 of the base capacity. After achieving user equilibrium by 20 iteration simulation processes, the results are: average travel time increasing from 139 to 145 minutes for Park& Ride riders. The result is as we expected, and the parking lot location can be tested as the same method. Based on the analysis above, we can build and maintain the regional intermodal network using DTALite/Nexta, which provide a comprehensive tool for transportation network analysis, strategies cooperating, and policies making. This is shown in Figure A-29.



	Demand (vehicle/hr)	avg_travel_time(min) Base capacity	1/3 of base capacity
Drive alone	2000	158	158
P&R	1000	139	145
transit	1000	137	142

Figure A-29: Average Travel Time Increase Due to Capacity Reduction [Source: Booz Allen]

D-RIDE Modeling

D-RIDE applications allow users to use wireless platforms, such as smartphones, to seamlessly connect passengers' demand to available vehicles in real-time ride-sharing systems. From the mathematical point of view, the D-RIDE algorithms fall into the category of the vehicle routing problem with pickup and delivery with time windows (a.k.a., VRPPDTW) problem which typically requires the use of complex optimization solvers even for a limited number of agents on medium scale networks. The ASU team proposed a new mathematical programming model for the VRPPDTW on vehicles' state-space-time transportation networks to model passenger-to-vehicle assignment and the related vehicle routing in real-world transportation networks. The necessary transportation network construction involves fully incorporating time-dependent link travel time between physical nodes, which can be caused by traffic congestion at different times of day. The next generation of transportation system initiatives aims to integrate various management strategies and control measures to achieve the mobility, environment, and sustainability goals. Several novel approaches have been recently suggested to reduce the undesirable effects of high traffic density of city roads, to name a few, improvement in public transportation, dynamic ride-sharing, and self-driving or fully connected vehicles that can follow system-optimized routes. By introducing the concept of D-RIDE, we can achieve a fundamental change in the transportation area. In a city with numerous travelers, each traveler ("he" hereafter) has his own traveling schedule. Instead of using his own car, the traveler can (by the aid of ride-sharing apps) bid and call a car just a few minutes before leaving his origin, or preschedule a car a day prior to his departure. The intelligent design of the shared vehicle system provides a traveler with a short waiting time even if he resides in a high-demand area. Currently, several real-time ride-sharing or more precisely app-based transportation network and taxi companies, such as Uber, Lyft, are serving passengers all around the world. There is a long list of advantages from this fully automated ride-sharing approach, e.g. reducing driver stress and driving cost, improving the mobility for passengers, increasing safety and fuel efficiency, and decreasing road congestion as well as reducing overall societal energy use and pollution.

Traditional solutions to the D-RIDE problems are typically time-consuming even for a relatively small case. To evaluate the potential benefits of D-RIDE at large scale, the ASU team proposed a new mathematical programming model for the vehicle routing problem with pickup and delivery with time windows (VRPPDTW) that can fully recognize time-dependent link travel time caused by traffic congestion at different times of day. Based on the Lagrangian relaxation solution framework, we further present a holistic optimization approach for matching passenger requests to transportation service providers, synchronizing transportation vehicle routing, and determining possibly system-optimal pricing (e.g., through Lagrangian multipliers) for balancing transportation demand satisfaction and resource needs on urban networks.

Let us first formulate PDPTW on the state-space-time transportation networks. In PDPTW, passengers may share their trip with each other; in other words, every vehicle, considering its capacity and the total routing cost, may serve as many passengers as possible if all passengers are picked up and dropped-off in their preferred time windows. Each transportation node has the potential to be the spot for picking up or dropping off a passenger. Likewise, vehicles' depot might be located at any node in the transportation network. To distinguish regular transportation nodes from passengers' and vehicles' origin and destination, we add a dummy node for each of passenger's origin, passenger's destination, vehicle v's origin depot, and vehicle v's destination depot to the physical transportation network. Each added dummy node is only connected to its corresponding physical transportation node by a link whose travel time can be interpreted as service time if the added dummy node is related to a passenger's origin or destination, and as preparation time if it is related to a vehicle's starting or ending depot. It is clear that each vehicle starts its route from its origin depot; it may pass through some transportation nodes or some passengers' origin and destination, and ends it to its destination depot. To construct such a network for vehicle v, it is sufficient to add dummy nodes corresponding to the starting and ending depots and origin and destination of those passengers who are going to be carried by vehicle v to the physical transportation network. Therefore, for each vehicle v, all possible passengers carrying states should be enumerated. Let C_v and P denote the maximum capacity of vehicle v and the total number of transportation requests, respectively; therefore, vehicle v can carry up to C_v number of passengers at the same time. Moreover, let w denote the passengers carrying state. Assume that each state has n number of elements which are representative of passengers' carrying status. If vehicle v carries passenger p, pth element of the state w is filled with passenger p id; otherwise, it is filled with a dash sign.

There is a unique state in which vehicle v does not carry any passenger (c_n^0). There are c_n^1 number of possible carrying states in which vehicle v only carries one passenger at a time. Likewise, there are c_n^i number of possible carrying states in which vehicle v carries i passengers at a time. Note that $i \leq C_v$. Therefore, the total number of possible carrying states is equal to $\sum_{i=0}^{C_v} c_n^i$. Note that according to the earliest departure time from the origin and the latest arrival time to the destination of different passengers, some of the possible carrying states might be infeasible.

Each vehicle starts its trip from empty state in which the vehicle does not carry any passenger. We call this state as the initial state (w_0). Each vertex is recognized by three different attributes: node id i, time stamp t, and passengers carrying state w. It is clear that each vertex (i, t, w) can be connected to vertex (j, s, w') by arc (i, j, t, s, w, w'). From the space-time transportation network, we already know (i, j, t, s). To find all feasible combination of (w, w'), it is sufficient to follow these rules:

- Rule 1. If vehicle v picks up passenger p, then pth element of state w is filled with a dash sign, whereas pth element of state w' is filled with passenger p id. Moreover, all other elements of w and w' should be the same.
- Rule 2. If vehicle v drop off passenger p, then pth element of state w' is filled with a dash sign, whereas pth element of state w is filled with passenger p id. Moreover, all other elements of w and w' should be the same.
- Rule 3. If vehicle v neither pickup nor drop off any passenger, all elements of w and w' should be the same.

Let o_p, d_p, o'_v, and d'_v denote passenger p's origin, passenger p's destination, vehicle v's origin, and vehicle v's destination, respectively. We use an illustrative example to demonstrate the concept of passengers' carrying state clearly. Suppose three requests with three different origin-destination pairs should be served. There is only one vehicle available for serving. The Vehicle can carry up to two passengers at the same time. Now we enumerate all different carrying states for the vehicle. The first state is the state in which the vehicle does not carry any passenger[_ _ _]. There are c_3^1 number of possible carrying states in which the vehicle only carries one passenger at time t:[p_1 _ _], [_ p_2 _], and [_ _ p_3]. Similarly, there are c_3^2 number of possible carrying states in which the vehicle carries two passengers at time t which are [p_1 p_2 _], [p_1 _ p_3], and [_ p_2 p_3]. Since the vehicle can carry up to two passengers at the same time, we stop enumeration here. Figure A-29 (a) illustrates carrying state [p_1 p_2 _], whereas Figure A-29 (b) demonstrates carrying state [_ p_2 _].

Every passenger p has a preferred time window for departure from his origin, $[a_p, b_p]$, and a desired time window for arrival at his destination, $[a'_p, b'_p]$, where a_p, b_p, a'_p, and b'_p are passenger p's earliest preferred departure time from his origin, latest preferred departure time from his origin, earliest preferred arrival time at his destination, and latest preferred arrival time at his destination, respectively. It is assumed that if vehicle v arrives at passenger p's origin node before time a_p, it must wait until the service is allowed to begin. Moreover, vehicle v's stop at passenger p's origin after time b_p is not allowed. Similarly, if vehicle v arrives at passenger p's destination node before time a'_p, it must wait until it is allowed to drop off passenger p, and vehicle v is not allowed to stop at passenger p's destination after time b'_p. In addition, vehicle v may wait at its own origin or destination depot. Each vehicle v also has the earliest departure time from its starting depot, e_v, and the latest arrival time at its ending depot, l_v.

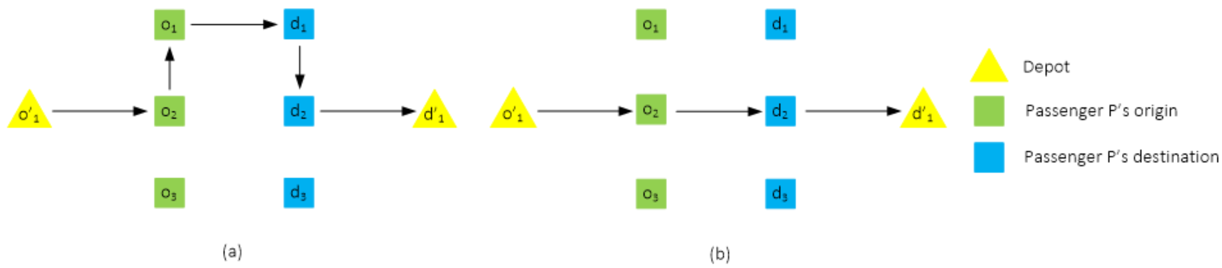


Figure A-30: (a) Passenger Carrying State $[p_1\, p_2\, \_]$; (b) Passenger Carrying State $[\_\, p_2\, \_]$ [Source: Booz Allen]

Let's assume that passenger 1 should be picked up in time window [4,7] and delivered in time window [9,12], whereas passenger 3's preferred time windows for being picked up and delivered are [20,24] and [25,29], respectively. So, it is obvious that passenger 1 and 3 cannot share their ride with each other and be transported at the same time by the same vehicle. Therefore, carrying state $[p_1\, \_\, p_3]$ is definitely infeasible.

Let's come back to the original problem with this assumption that all possible carrying states are feasible; then to find all feasible (w, w'), we need to examine all possible combinations of w and w'. If $w_0, w_1, w_2, w_3, w_4, w_5$, and w_6 are all carrying states $[\_\,\_\,\_]$, $[p_1\,\_\,\_]$, $[\_\, p_2\,\_]$, $[\_\,\_\, p_3]$, $[p_1\, p_2\,\_]$, $[p_1\,\_\, p_3]$, and $[\_\, p_2\, p_3]$, Table A-4 brings all possible combinations of these states. All possible passengers' carrying states transition (pick up or drop off) are illustrated in one graph in Figure A-31.

Table A-4: D-RIDE Possible Combinations

w \ w'	$[\_\,\_\,\_]$	$[p_1\,\_\,\_]$	$[\_\,p_2\,\_]$	$[\_\,\_\,p_3]$	$[p_1\,p_2\,\_]$	$[p_1\,\_\,p_3]$	$[\_\,p_2\,p_3]$
$[\_\,\_\,\_]$	No change	Pick up	Pick up	Pick up	impossible	impossible	impossible
$[p_1\,\_\,\_]$	Drop off	No change	impossible	impossible	Pick up	Pick up	impossible
$[\_\,p_2\,\_]$	Drop off	impossible	No change	impossible	Pick up	impossible	Pick up
$[\_\,\_\,p_3]$	Drop off	impossible	impossible	No change	impossible	Pick up	Pick up
$[p_1\,p_2\,\_]$	impossible	Drop off	Drop off	impossible	No change	impossible	impossible
$[p_1\,\_\,p_3]$	impossible	Drop off	impossible	Drop off	impossible	No change	impossible
$[\_\,p_2\,p_3]$	impossible	impossible	Drop off	Drop off	impossible	impossible	No change

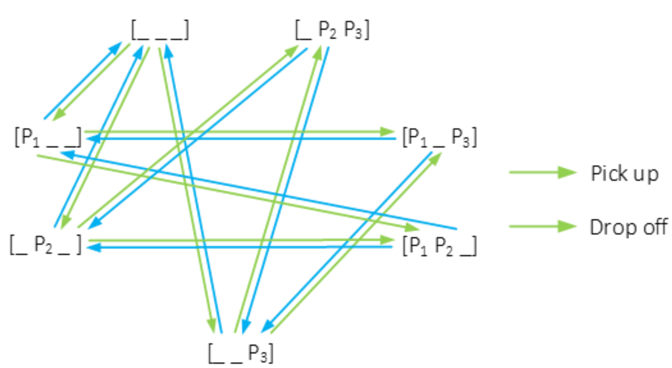


Figure A-31: All Possible Passengers' Carrying States Transition (Pick-Up or Drop-Off) [Source: Booz Allen]

It is quite possible that some requests could not be satisfied at all due to different reasons such as the total number of vehicles serving passengers is not enough to satisfy all the demands, or serving some passengers due to their desired departure and arrival time windows is impossible. To avoid infeasibility, we define a virtual vehicle for each passenger exclusively. Virtual vehicle v_p^* is activated to serve passenger p if there is no available actual vehicle to satisfy his demand. We assume that both starting and ending depot of virtual vehicle v_p^* are located exactly where passenger p is going to be picked up. Therefore, similar to actual vehicles, we add a dummy node for each of virtual vehicle v^*'s origin depot and vehicle v^*'s destination depot to the physical transportation network. Each added dummy node is only connected to its corresponding physical transportation node by a link whose travel time can be interpreted as preparation time. If there is an actual vehicle available to satisfy passenger p's request, virtual vehicle v_p^* remains inactive; otherwise, virtual vehicle v_p^* like an actual vehicle starts its route from its starting depot, picks up passenger p, delivers him to his destination, and then comes back to its ending depot.

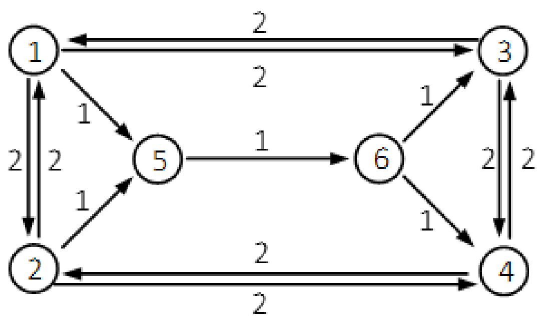


Figure A-32: Six-Node Transportation Network [Source: Booz Allen]

To better illustrate the proposed algorithm, the ASU team used an illustrative example to demonstrate key modeling features of constructed state-space-time networks. Consider a physical transportation network that consists of six nodes presented in Figure A-32. Each link in this network is associated with a transportation cost c_{ij} and a travel time t_{ij}. Number written on each link is representative of t_{ij}. To simplify this example, it is assumed that the travel time, t_{ij}, remains constant over time. Suppose two requests with two origin-destination pairs should be served. For simplicity, it is assumed that both passengers have the same origin (node 2) and the same drop-off node (node 3). There is only one vehicle available for serving. Moreover, it is assumed that the vehicle starts its route from node 4 and ends it to node 1. Passenger 1 should be picked up in time window $[4,7]$ and dropped off in time window $[9,12]$, while passenger 2 preferred departure and arrival time windows are $[10,12]$ and $[15,17]$, respectively.

To construct a network consists of transportation nodes and origin-destination pairs of passengers and vehicles, it is sufficient to add a dummy node for each of passenger's origin and destination, and vehicle's origin and destination to the physical transportation network and related links as shown in Figure A-32. Note that the added node is only connected to its corresponding physical transportation node by a link whose travel time is assumed a unit of time in this example. Let us assume that the maximum capacity of the vehicle is 2. Therefore, the vehicle can carry up to two passengers at the same time. Figure A-32 and Figure A-33 show physical and state-space-time transportation networks with origin-destination pairs for passengers and the vehicle. To construct a state-space-time network, the time horizon is discretized into a series of time intervals with the same time length. We assume that a unit of time has one-minute length. To avoid more complexity in the vehicle's state-space-time network illustrated in Figure A-33, only those arcs serving passenger 1's request and those arcs constituting the shortest path from passenger 1's origin to his destination are demonstrated.

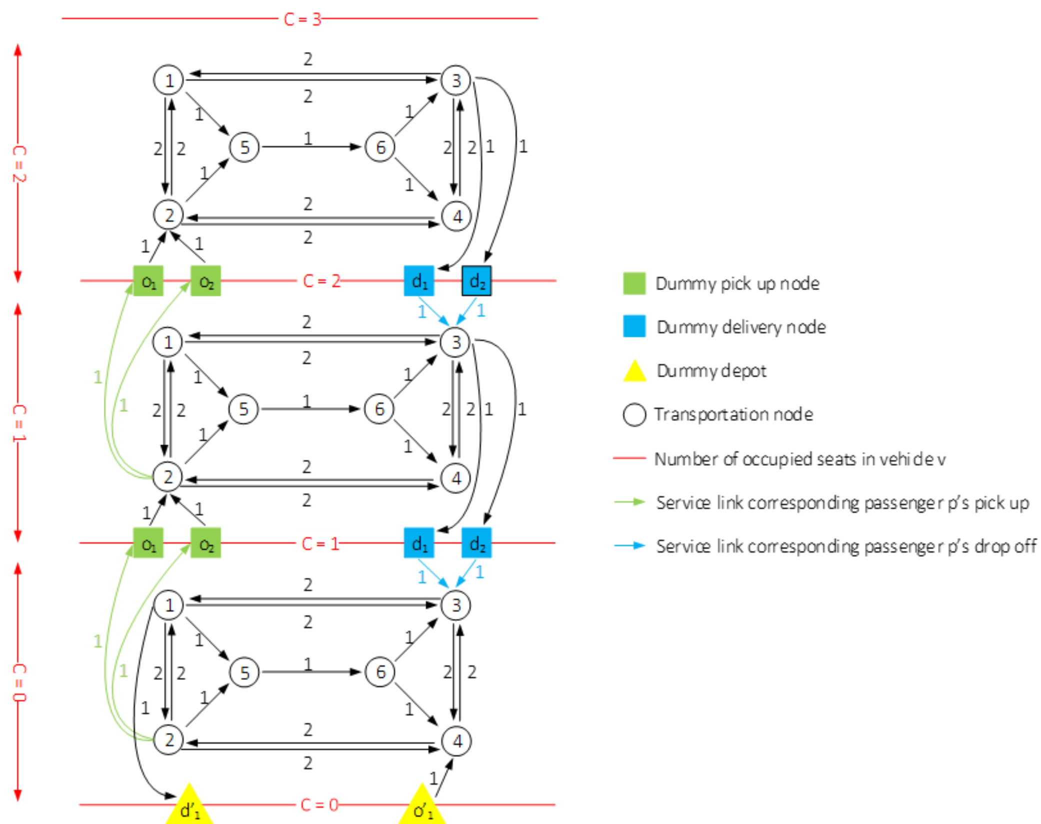


Figure A-33: Physical Transportation Network with Origin-Destination Pairs for Passengers and the Vehicle [Source: Booz Allen]

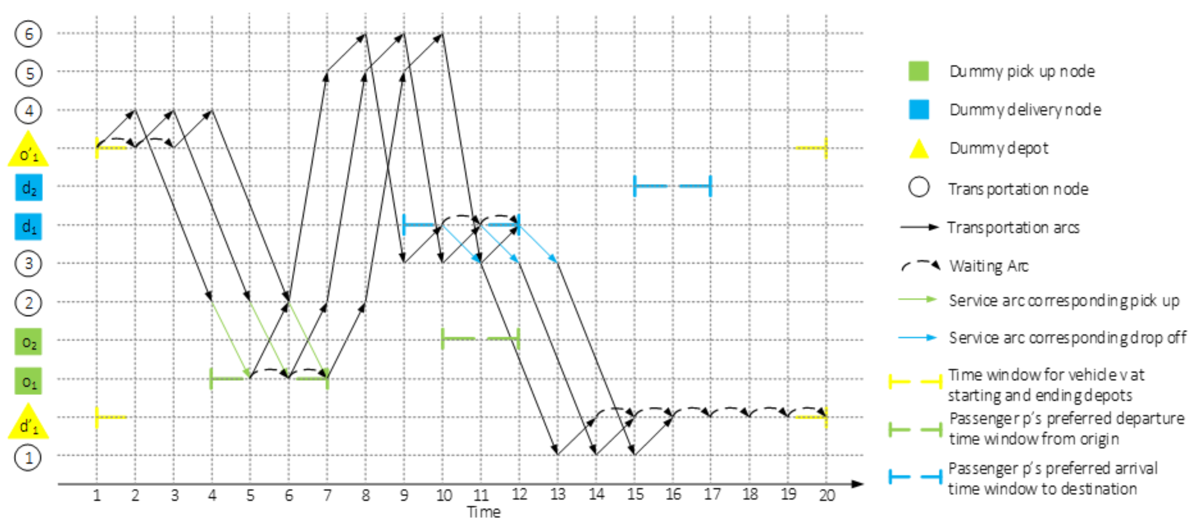


Figure A-34: Vehicle's Space-Time Network [Source: Booz Allen]

Appendix I. AMS Project Publication List

A list of all the publications from the AMS project is provided below:

Table A-5: AMS Project Publications

No.	Document Title	JPO Publication #
1	ATDM-DMA AMS Testbed Project: Detailed AMS Requirements	FHWA-JPO-16-369
2	ATDM-DMA AMS Testbed Project: AMS Testbed Selection Report	FHWA-JPO-16-355
3	ATDM-DMA AMS Testbed Project: Analysis Plan for San Mateo Testbed	FHWA-JPO-16-370
4	ATDM-DMA AMS Testbed Project: Analysis Plan for Pasadena Testbed	FHWA-JPO-16-371
5	ATDM-DMA AMS Testbed Project: Analysis Plan for Phoenix Testbed	FHWA-JPO-16-372
6	ATDM-DMA AMS Testbed Project: Analysis Plan for Dallas Testbed	FHWA-JPO-16-373
7	ATDM-DMA AMS Testbed Project: Analysis Plan for Chicago Testbed	FHWA-JPO-16-374
8	ATDM-DMA AMS Testbed Project: Analysis Plan for San Diego Testbed	FHWA-JPO-16-375
9	ATDM-DMA AMS Testbed Project: AMS Evaluation Plan	FHWA-JPO-16-376
10	ATDM-DMA AMS Testbed Project: Calibration Report for San Mateo Testbed	FHWA-JPO-16-377
11	ATDM-DMA AMS Testbed Project: Calibration Report for Pasadena Testbed	FHWA-JPO-16-378
12	ATDM-DMA AMS Testbed Project: Calibration Report for Phoenix Testbed	FHWA-JPO-16-379
13	ATDM-DMA AMS Testbed Project: Calibration Report for Dallas Testbed	FHWA-JPO-16-380
14	ATDM-DMA AMS Testbed Project: Calibration Report for Chicago Testbed	FHWA-JPO-16-381
15	ATDM-DMA AMS Testbed Project: Calibration Report for San Diego Testbed	FHWA-JPO-16-382
16	ATDM-DMA AMS Testbed Project: Evaluation Report for DMA Program	FHWA-JPO-16-383
17	ATDM-DMA AMS Testbed Project: Evaluation Summary for DMA Program	FHWA-JPO-16-384

No.	Document Title	JPO Publication #
18	ATDM-DMA AMS Testbed Project: Evaluation Report for ATDM Program	FHWA-JPO-16-385
19	ATDM-DMA AMS Testbed Project: Evaluation Summary for ATDM Program	FHWA-JPO-16-386
20	ATDM-DMA AMS Testbed Project: Evaluation Report for Chicago Testbed	FHWA-JPO-16-387
21	ATDM-DMA AMS Testbed Project: Evaluation Summary for Chicago Testbed	FHWA-JPO-16-388
22	ATDM-DMA AMS Testbed Project: Evaluation Report for San Diego Testbed	FHWA-JPO-16-389
23	ATDM-DMA AMS Testbed Project: Evaluation Summary for San Diego Testbed	FHWA-JPO-16-390
24	ATDM-DMA AMS Testbed Project: White Paper on AMS Gaps, Challenges, and Future Research	FHWA-JPO-16-391

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