

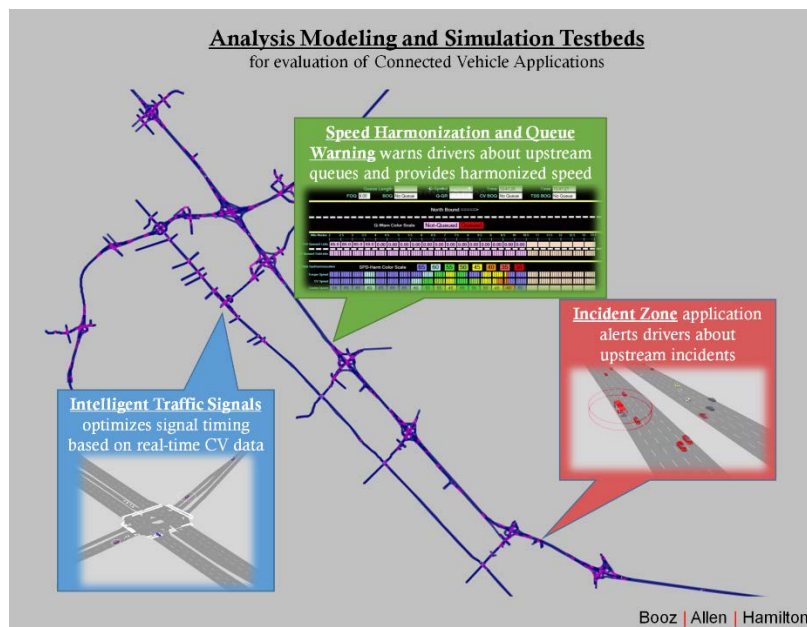
Analysis, Modeling, and Simulation (AMS) Testbed Development and Evaluation to Support Dynamic Mobility Applications (DMA) and Active Transportation and Demand Management (ATDM) Programs

Evaluation Summary for DMA Program

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Final Report — August 2017

FHWA-JPO-16-384



U.S. Department of Transportation

Produced by
Booz Allen Hamilton for

U.S. Department of Transportation
Intelligent Transportation System (ITS) Joint Program Office (JPO)

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Technical Report Documentation Page

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|--|--|---|------------------|
| 1. Report No. FHWA-JPO-16-384 | 2. Government Accession No. | 3. Recipient's Catalog No. | |
| 4. Title and Subtitle Analysis, Modeling, and Simulation (AMS) Testbed Development and Evaluation to Support Dynamic Mobility Applications (DMA) and Active Transportation and Demand Management (ATDM) Programs — Evaluation Summary for DMA Program | | 5. Report Date July 2017 | |
| | | 6. Performing Organization Code | |
| 7. Author(s) Balaji Yelchuru and Raj Kamalanathsharma | | 8. Performing Organization Report No. | |
| 9. Performing Organization Name And Address Booz Allen Hamilton, 20 M Street SE, Suite 1000 Washington, DC – 20003 | | 10. Work Unit No. (TRAIIS) | |
| | | 11. Contract or Grant No. DTFH61-12-D-00041 | |
| 12. Sponsoring Agency Name and Address U.S. Department of Transportation Intelligent Transportation Systems—Joint Program Office (ITS JPO) 1200 New Jersey Avenue, SE Washington, DC 20590 | | 13. Type of Report and Period Covered Summary Report – Oct 2014 to Feb 2017 | |
| | | 14. Sponsoring Agency Code | |
| 15. Supplementary Notes FHWA Government Task Managers: James Colyar, Roemer Alfelor | | | |
| 16. Abstract The primary objective of this project is to develop multiple simulation testbeds/transportation models to evaluate the impacts of Dynamic Mobility Application (DMA) connected vehicle applications and Active Transportation and Demand management (ATDM) strategies. While the project aims at evaluating both DMA applications and ATDM strategies, the primary purpose of this report is to summarize the evaluation done in terms of DMA applications using the AMS testbeds. The full DMA evaluation results are contained in a separate report entitled <i>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</i> (FHWA-JPO-16-383). Primarily, San Mateo and Phoenix were used as DMA-centric testbeds and were used to assess the DMA applications under various scenarios and combinations of applications, communication attributes and evaluation attributes to answer a set of research questions set forth by the USDOT. Chicago and San Diego Testbeds were also used to conduct some additional DMA analysis and are included in this report. | | | |
| 17. Key Words DMA, Analysis Modeling and Simulation (AMS), Connected Vehicles, San Mateo, Phoenix, Chicago, San Diego | | 18. Distribution Statement | |
| 19. Security Class if. (of this report) | 20. Security Class if. (of this page) | 21. No. of Pages 19 | 22. Price |

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AMS Testbed Project Overview

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. Effective 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 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. Rather than a single Testbed, it is desirable to identify a portfolio of AMS Testbeds in order to (1) capture a wider range of geographic, environmental and operational conditions under which to examine most appropriate ATDM and DMA strategy bundles; (2) add robustness to the analysis results; and (3) mitigate the risks posed by a single Testbed approach. At the conclusion of the initial selection process, six testbeds were selected to form a diversified portfolio to achieve rigorous DMA bundle and ATDM strategy evaluation. They are: (1) San Mateo, CA, (2) Pasadena, CA, (3) Dallas, TX, (4) Phoenix, AZ, (5) Chicago, IL and (6) San Diego, CA. Chicago and San Diego Testbeds were not a part of the original AMS Testbed selection process but were added later owing to their significance in covering some of the operational conditions and predictive methods that were not covered with the other four testbeds. Figure 1 shows the six testbeds extending over the United States.



Figure 1. Testbeds Used for AMS Project [Source: Booz Allen]

Table 1 presents an overview of the Testbeds including their geographic details, description of the facility as well as the primary application/strategy type that is included in the Testbed.

Table 1. Overview of Testbeds

| <i>Testbed</i> | <i>Geographic Details</i> | <i>Facility Type</i> | <i>Applications / Strategies</i> |
|----------------------|---|---|---|
| San Mateo, CA | 8.5-mile-long section of US 101 freeway and a parallel SR 82 arterial. | Freeway and Arterial | DMA only |
| Pasadena, CA | Covers an area of 11 square miles and includes two major freeways – I-210 and CA-134 along with arterials and collectors between these. | Freeways and arterial system. | DMA and ATDM |
| Dallas, TX | A corridor network comprised of a 21-mile-long section of US-75 freeway and associated frontage roads, transit lines, arterial streets etc. | Freeways/Arterials and Transit (Light-Rail and buses) | ATDM only |
| Phoenix, AZ | Covers the entire metropolitan region under Maricopa County including freeways, arterials, light rail lines etc. | Freeways/Arterials and Transit (Light-Rail and buses) | DMA and ATDM |
| Chicago, IL | Freeways and arterials in the downtown Chicago area including I-90, I-94, I-290. | Freeways/Arterials | DMA, ATDM and Weather-related strategies. |
| San Diego, CA | 22 miles of I-15 freeway and associated arterial feeders covering San Diego, Poway and Escondido | Freeway and Arterial System | DMA and ATDM |

While the project aims to evaluate both DMA applications and ATDM strategies, the primary purpose of this report is to summarize 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. Chicago and San Diego Testbeds were also used to conduct some additional DMA analysis and are included in this report. 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.

The study addressed important research questions regarding the effectiveness of specific DMA applications under different operational conditions in a simulated testbed environment. The research questions fall under the following categories: (1) synergies and conflicts among applications, (2) impact on application performance of different facility types under varied operational conditions, (3) suitability of different messaging protocols and communication technologies to different DMA applications, (4) impact of communication latency and loss on effectiveness of certain DMA applications, (5) deployment readiness of applications in terms of application maturity as well as RSE/DSRC coverage, and (6) analysis of deployment costs and benefits. Please note that quantitative research was utilized to support some of these categories of research questions.

DMA-specific Testbeds Overview

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 while San Diego and Chicago involved limited modeling of DMA applications as well. These four testbeds are covered in this report.

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.

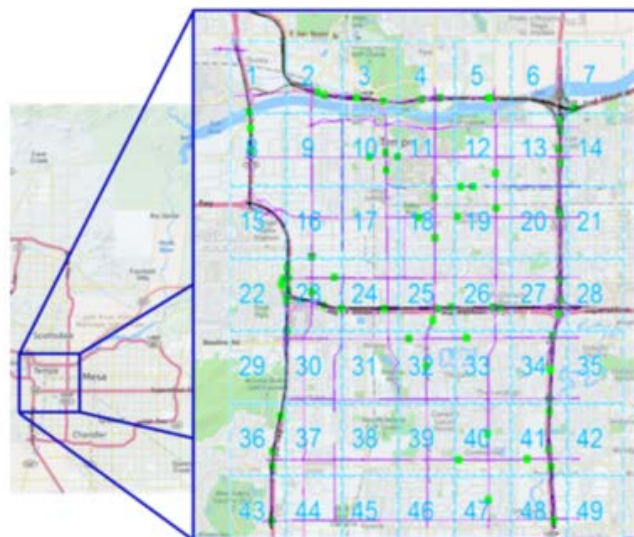
The Chicago Testbed network was extracted from the entire Chicago Metropolitan Area to enhance the estimation and prediction performance during the implementation procedure. This testbed was developed for the Chicago core area, which covers around 15 miles from north to south and 10 miles from east to west. A unique feature of the Chicago testbed along the spectrum of conditions exemplified by the five testbeds is the occurrence of severe winter weather, particularly snow events which are common for at least four months of the year. The Testbed area includes the Chicago downtown area, suburbs and cities north of Chicago connecting with major highway sections. These highway sections include the Kennedy Expressway (I-90), the major road connecting downtown Chicago with O'Hare airport, the Edens Expressway (I-94), the major north-south highway connecting downtown Chicago with many of the suburbs and cities north of Chicago, the Dwight D. Eisenhower Expressway (I-290), the major east-west highway connecting downtown Chicago with the western suburbs, and Lakeshore Drive, the mostly freeway-standard expressway running parallel with and alongside the shoreline of Lake Michigan through Chicago.

The San Diego Testbed facility comprises of a 22-mile stretch of interstate I-15 and associated parallel arterials and extends from the interchange with SR 78 in the north to the interchange with SR-163 in the south. The current I-15 corridor operates with both general-purpose (GP) lanes and four express lanes

from the Beethoven Drive DAR to the southern extent of the model. These lanes currently run with two northbound lanes and two southbound lanes and are free to vehicles travelling with two or more passengers in the car (High-Occupancy Vehicles, or HOVs); they also allow Single Occupancy Vehicles (SOV) to use the lanes for a fee, using a variable toll price scheme making them High Occupancy Tolloed (HOT) lanes. In addition, it is possible to change the lane configuration of the express lanes with the use of barrier transfer (zipper) vehicles and the Reversible Lane Changing System (RLCS).



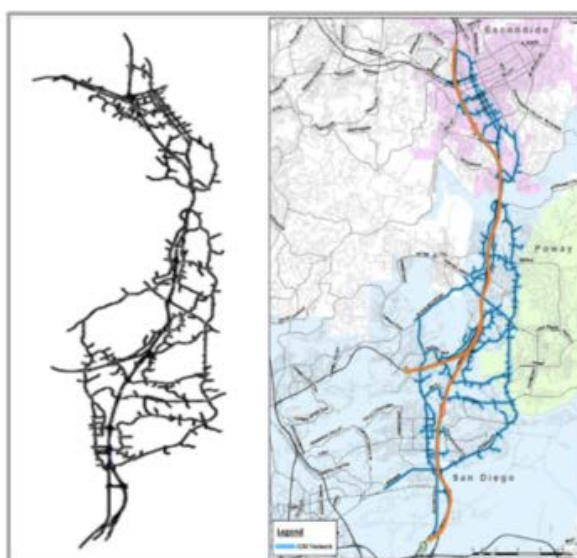
(a) San Mateo Testbed



(b) Phoenix Testbed



(c) Chicago Testbed



(d) San Diego Testbed

Figure 2: Four Testbed Networks Used for DMA Research [Source: Booz Allen, NWU, TSS]

Full details on the evaluation approach and modeling methodology is provided in *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 the DMA Program, FHWA-JPO-16-383, July 2017.*

Summary of Operational Conditions

For each of the testbeds, cluster analyses were done to identify commonly occurring operational conditions by finding out representative days using historical data. Cluster analysis was used to reduce some of the structure and to determine the best operational condition to represent the whole spectrum of traffic conditions for the evaluations of DMA application bundles.

Depending on the complexity of the testbed operational capabilities, three to six representative operational conditions are identified using cluster analysis. These are listed in Table 2. In addition, a few hypothetical operational conditions are assumed for some testbeds to demonstrate some hypothetical operational condition that is not representative of that region. Operational conditions are prioritized based on their match with the representative day's data. Please note that the Operational Conditions denoted by asterisk represents hypothetical (non-existing) conditions.

Table 2. Operational Conditions for Each Testbed

| Op. Con. | San Mateo | Phoenix | Chicago | San Diego |
|-----------------|--|--|--|--|
| OC-1 | Medium Demand, Major Incidents, Dry Weather Conditions | High Demand, Minor Incidents, Dry Weather Conditions | High Demand, No Incidents, Dry Weather Conditions | Southbound (AM), Medium Demand, Medium Incident |
| OC-2 | Medium Demand, Major Incidents, Wet Weather Conditions | High Demand, Major Incidents, Dry Weather Conditions | High Demand, No Incidents, Wet to Snowy Weather Conditions | Southbound (AM), Medium Demand and High Incident |
| OC-3 | Medium Demand, No Incidents, Dry Weather Conditions | Low Demand, Minor Incidents, Dry Weather Conditions. | Medium to High Demand, No Incidents, Snowy Weather Conditions | Northbound (PM), High Demand, High Incident |
| OC-4 | High Demand, Minor Incidents, Dry Weather Conditions | High Demand, Medium Incidents, Wet Weather Conditions. | Low to Medium Demand, No Incidents and Snowy Weather Conditions | Northbound (PM), High Demand, Medium Incident |
| OC-5 | | | Medium to High Demand, No Incidents, Snowy Weather Conditions. | |
| HO-1* | | | Medium to High Demand, Minor Incidents, Snowy Weather Conditions | |
| HO-2* | | | | |

Table 3 shows the operational conditions attributes with respect to demand, incident severity and weather conditions across Testbeds.

Table 3. Operational Conditions Attributes Across Testbeds

| <i>Attribute</i> | <i>Value</i> | <i>San Mateo</i> | <i>Phoenix</i> | <i>Chicago</i> | <i>San Diego</i> |
|---------------------------|---------------|------------------|----------------|----------------|------------------|
| Demand | Low | | • | • | |
| | Medium | • | | • | • |
| | High | • | • | • | • |
| Incident Severity | None | • | | • | |
| | Low | • | • | | |
| | Medium | | • | | • |
| | Major | • | • | | • |
| Weather Conditions | Dry | • | • | • | • |
| | Light Rain | • | | • | |
| | Moderate Rain | | • | • | |
| | Heavy Rain | | | • | |
| | Moderate Snow | | | • | |
| | Heavy Snow | | | • | |

DMA Applications Modeled

Specifically, this evaluation includes six bundles of applications. Some of the applications are prototyped together through four simulation-based testbeds. The six bundles are pictured in Figure 3.

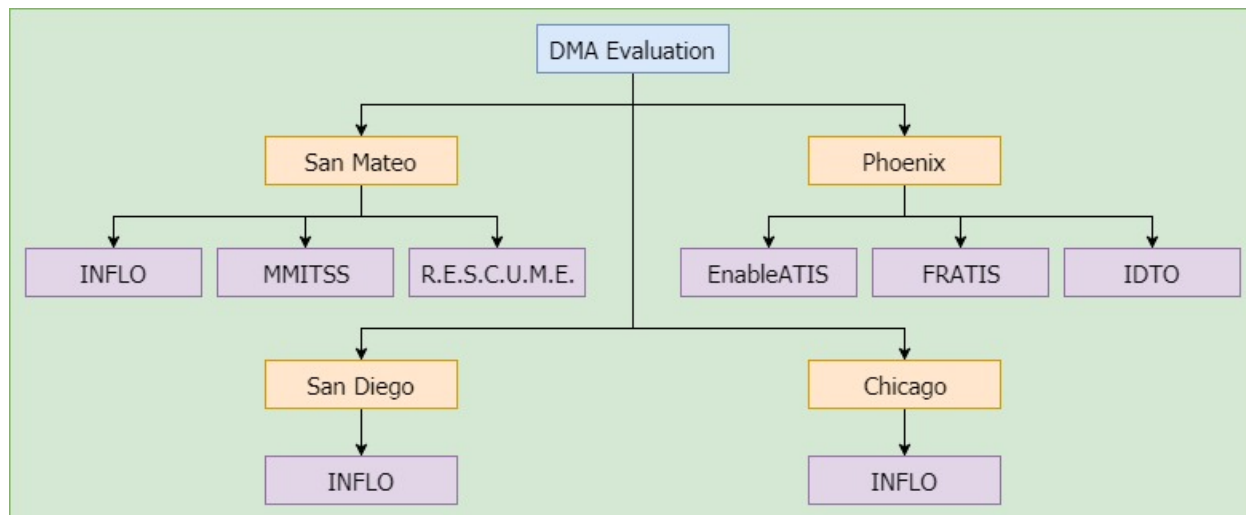


Figure 3: Application Bundles [Source: Booz Allen]

They application bundles are:

1. INFLO – Intelligent Network Flow Optimization
 - a. Q-WARN – Queue Warning
 - b. SPD-HARM – Dynamic Speed Harmonization
 - c. CACC – Cooperative Adaptive Cruise Control

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.

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.

Summary of Findings and Conclusions

In this section, the major findings and conclusions, with respect to DMA evaluation, are summarized. The results are summarized and categorized according to the different types of research questions that were set forth by the USDOT. The full DMA evaluation results are contained in the report *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 (FHWA-JPO-16-383)*.

Connected Vehicle Technology versus Legacy Systems

This analysis was primarily aimed at answering the impact of data from CV technology on the DMA applications versus the impact of data from legacy systems. Specifically, INFLO and MMITSS applications were assessed under this analysis, using both San Mateo and Chicago Testbeds

It was found that 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 defined 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 the San Mateo Testbed, legacy system data contributes to most benefits from INFLO and MMITSS at lower market penetration and CV data at higher market penetration. 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.

For the Chicago Testbed, flow characteristics in a connected environment were identified based on a microscopic simulation tool. The calibrated speed-density relations were utilized in a mesoscopic simulation tool to study the network-wide effects of connected vehicles. Observations from the simulated traffic data with only connected vehicles and no speed harmonization show that with increase in market penetration rate (MPR) of connected vehicles, the network attains a lower maximum density and exhibits an increased flow rate for the same density level. Thus, a highly-connected environment has potential to help a congested network recover from flow breakdown and avoid gridlock. Moreover, the effects of connected vehicles become more pronounced as demand increases. They were found to be effective in improving the travel time reliability. Connected vehicles reduce the mean travel time while making the system more reliable. Overall, connected vehicles can improve the system's performance by increasing throughput and enhancing travel time reliability at all demand levels. With speed harmonization, increase in throughput was observed. Speed harmonization in a connected environment provides a slight improvement in the throughput. Travel speed was found to increase and become more uniform as the variation of speed was reduced.

Synergies and Conflicts between DMA Applications

In this category, research questions evaluating the benefits of implementing DMA applications under combination or isolation are assessed for the different operational conditions to understand their synergistic pairs and conflicting pairs.

In order to assess the impact of application combinations, MMITSS, INC-ZONE, and INFLO were assessed in isolation and in combination using the San Mateo Testbed. 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).

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 penetration 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 assessed combinations of CACC with SPD-HARM using the San Diego Testbed. Synergy between SPD-HARM and CACC appeared to be minimal. At all penetration rates the effect of SPD-HARM seems to prevail over CACC, even though the vehicles engaged by CACC are not affected by SPD-HARM messages, and in fact it seems to neutralize the benefit in terms of traffic performance that CACC produces when deployed alone. At low penetration rates, the results show some synergy in terms of shockwave reduction; however, at high penetration rates the shockwave reduction is similar to that produced by SPD-HARM alone, and at 50% penetration rate the two DMA applications seem to produce a conflict, with lower traffic performance than each application alone, and less shockwave reduction than SPD-HARM alone. The explanation is that at 50% penetration rate CACC platoons are long enough to constitute an impediment for lane-changing of non-connected vehicles, and the addition of SPD-HARM introduces a heterogeneity in the desired speed of non-connected vehicles, which are not affected by SPD-HARM, compared to connected vehicles, which are affected; this increases the desire for non-connected vehicles to overtake connected vehicles, and thus exacerbates the lane-changing issue. Please note that this results cannot be generalized, but for this specific implementation. Depending on the algorithm that determines harmonized speeds, the performance of the application could vary.

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. Table 4 and Table 5 show the mapping of applications and their preferred facility types. The facility types are identified based on the application's functionality and design.

Table 4: 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 for the San Mateo Testbed For the San Diego, the best performing operation condition was Northbound (PM) +Medium Demand + Medium Incident for the SPD-HARM application and Northbound (PM) +Medium Demand + High Incident for the CACC application. |
| 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 5: 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 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 and Communication Technology

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.

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.

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.

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 6, certain applications/bundles that require localized deployment work best with DSRC, whereas others work better with cellular.

Table 6: Summary of Preferred Medium for DMA Applications

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

Communication Latency and Losses

Communication latency and losses could significantly affect the performance of applications. To assess this, these two communication attributes were modeled within San Mateo and San Diego Testbeds.

For San Mateo, Trajectory Converter Analysis Tool was used to assess 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 dis-benefits to the system. The impact of communication losses in INC-ZONE and INFLO were similar to reduction in market penetration.

For San Diego, AIMSUN API was used to incorporate latencies and losses, and was analyzed for SPD-HARM application. Unlike San Mateo, San Diego testbed displayed minimal impacts when latencies of 1 second and 3 second were injected into the communications model. This might be due to differences in the way latency is modeled between the two testbeds. As far as the impact of message loss is concerned, it was found that at lower market penetrations, message loss has a higher impact on benefits than at higher market penetrations.

Deployment Readiness and RSE/DSRC Footprint Analysis

In order to assess the deployment readiness, the project team hypothesized that application and bundle performance will improve as more and more vehicles are equipped. 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 approach² 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.

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. 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. 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

² Harding et al., NHTSA, Vehicle-to-Vehicle Communications: Readiness of V2V Technology for Application, DOT HS 812 014, August 2014.

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).

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.

Analysis of Deployment Costs and Benefits

This project also 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.

U.S. Department of Transportation
ITS Joint Program Office-HOIT
1200 New Jersey Avenue, SE
Washington, DC 20590

Toll-Free "Help Line" 866-367-7487
www.its.dot.gov

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